US Army Corps of Engineers
Waterways Experiment Station

Wetlands Research Program Technical Report WRP-SM-12

Framework for Wetland Systems Management: Earth Resources Perspective

by Andrew G. Warne, Lawson M. Smith

19960201 018

October 1995 – Final Report

The following two letters used as part of the number designating technical reports of research published under the Wetlands Research Program identify the area under which the report was prepared:

	Task		Task
CP	Critical Processes	RE	Restoration & Establishment
DE	Delineation & Evaluation	SM	Stewardship & Management

Wetlands Research Program

Technical Report WRP-SM-12
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Framework for Wetland Systems Management: Earth Resources Perspective

by Andrew G. Warne, Lawson M. Smith

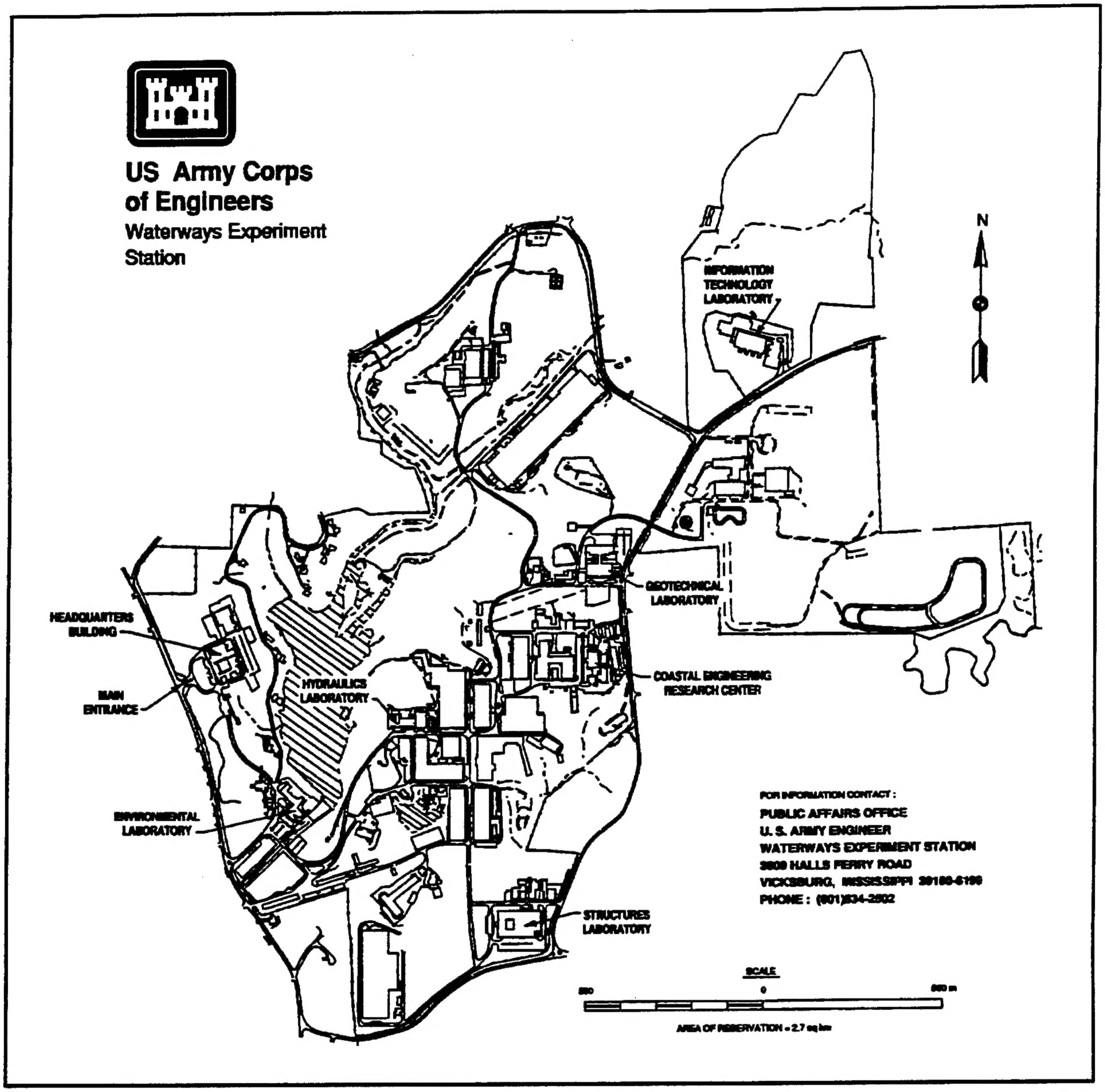
U.S. Army Corps of Engineers
Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

Final report

Approved for public release; distribution is unlimited

Prepared for U.S. Army Corps of Engineers
Washington, DC 20314-1000

Under WRP Work Unit 32766



Waterways Experiment Station Cataloging-in-Publication Data

Warne, Andrew G.
Framework for wetland systems management : earth resources perspective / by Andrew G. Warne, Lawson M. Smith ; prepared for U.S. Army Corps of Engineers.
154 p. : ill. ; 28 cm. — (Technical report ; WRP-SM-12) (Wetlands Research Program technical report ; WRP-SM-12)
Includes bibliographic references.
1. Wetlands — Management. 2. Ecosystem management. 3. Natural resources — Management. I. Smith, Lawson M. II. United States. Army. Corps of Engineers. III. U.S. Army Engineer Waterways Experiment Station. IV. Wetlands Research Program (U.S.) VI. Title. VII. Series: Wetlands Research Program technical report ; WRP-SM-12. VIII. Series: Technical report (U.S. Army Engineer Waterways Experiment Station) ; WRP-SM-12.
TA7 W34 no.WRP-SM-12

Corps of Engineers Research Report Summary, October 1995

Wetlands Management

Framework for Wetland Systems Management: Earth Resources Perspective (TR WRP-SM-12)

ISSUE:

Wetlands have traditionally been managed as individual entities with insufficient consideration of the role of the larger landscape on the wetland or the wetland as a subsystem in the larger landscape system. It is commonly recognized, however, that wetlands are critical elements of the landscape and that the landscape is inextricably linked to specific wetland functions, which are the object of wetland management.

RESEARCH:

A framework for managing wetlands in the context of the larger landscape was developed by focusing on the role of landscape level conditions and processes on wetland functions. The management framework was developed from the perspective of applied earth science, concentrating on climatological, geological, and hydrological aspect of wetland/ landscape conditions, processes, and interactions with the idea that these concepts be combined with the abundance of information on the biological management of wetlands.

SUMMARY:

This document is an initial step toward establishing a comprehensive and systematic framework to manage wetlands and their functions in a landscape context. Specifically, the framework provides guidance for formulating and implementing a comprehensive wetland management program. Establishing such a program has three principal phases: plan formulation, information development, and program implementation. Formulation involves assessing available fiscal and human resources, identifying priorities and goals within resource limits, and organizing an initial working plan for fulfilling prescribed goals. Information development involves evaluating available data, determining data gaps, establishing a monitoring program, and compiling data for assessment of the wetland landscape. Implementation leads to conclusions and development of a wetland management strategy for maintaining and enhancing wetland functions.

This document describes a variety of principles and methods for evaluating landscape and wetland systems. In particular, aspects of climate, geology, and hydrology are discussed.

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Contents

List of Figures

List of Tables

Preface

The work described in this report was authorized by Headquarters, U.S. Army Corps of Engineers (HQUSACE), as part of the Stewardship and Management Task Area of the Wetlands Research Program (WRP). The work was performed under Work Unit 32766, "Wetlands Stewardship and Management Demonstration Areas," for which Mr. Chester O. Martin was Technical Manager. Ms. Denise White (CECW-ON) was the WRP Technical Monitor for this work.

Mr. Dave Mathis was the WRP Coordinator at the Directorate of Research and Development, HQUSACE; Dr. William L. Klesch (CECW-PO) served as the WRP Technical Monitors' Representative. Dr. Russell F. Theriot (CEWES-EP-W) was the Wetlands Research Program Manager; and Mr. Martin, U.S. Army Engineer Waterway Experiment Station (WES), was the Task Area Manager.

The work was performed in the Geotechnical Laboratory (GL), WES, by Drs. Andrew G. Warne and Lawson M. Smith, Engineering Geology Branch. Their work was documented under the general supervision of Mr. Joseph Gatz, Chief, Engineering Geology Branch; Dr. Arley G. Franklin, Chief, Earthquake Engineering and Geosciences Division; and Dr. W. F. Marcuson III, Director, GL.

Suggestions on the manuscript were provided by Dr. L. Jean O'Neil and Mr. R. Daniel Smith, EL, and Mr. Joseph Gatz and Dr. Mary Ellen Hynes, GL, WES.

During the publication of this report, Dr. Robert W. Whalin was the Director of WES. COL Bruce K. Howard, EN, was the Commander.

This report should be cited as follows:

> Warne, Andrew G., and Smith, Lawson M. (1995). "Framework for Wetland Systems Management: Earth Resources Perspective," Technical Report WRP-SM-12, U.S. Army Engineer Waterways Experiment Station, Vicksburg, MS.

1 Introduction

The capacity of wetlands to provide specific functions is inextricably linked to landscape forms and processes. To date, however, no management program treats wetlands as interactive components of landscapes. This document is an initial step toward establishing a comprehensive and systematic earth resource framework to manage wetlands and their functions in a landscape context.

Specifically, the framework provides guidance for formulating and implementing a comprehensive wetland management program (Figure 1). Establishing such a program has three principal phases: (a) plan formulation, (b) information development, and (c) program implementation. Formulating a successful wetland management program involves assessing available fiscal and human resources, identifying priorities and goals within resource limits, and formulating an initial working plan capable of fulfilling prescribed goals. Information development involves evaluating available data, determining data gaps, establishing a monitoring program, and compiling data for assessment of the wetland landscape. Implementing a wetland assessment program leads to conclusions and development of a wetland management strategy that is capable of maintaining and enhancing wetland functions. The wetland systems management framework is described in more detail in Chapter 6.

An effective wetland management program must be based upon thorough understanding of the many facets of landscape systems. This document describes a variety of principles and methods for evaluating landscape and wetland systems. In particular, aspects of climate, geology, and hydrology are discussed. Descriptions of landscape monitoring and analysis techniques in this document are intended to serve as a brief introduction. Actual implementation of many of the techniques described herein require a great deal of knowledge and skill, and the reader is encouraged to refer to documents cited in the text and to seek the advice of experts when applying these procedures. This document intends to provide a fundamental understanding of earth sciences so that wetland managers can recognize the principal climatologic, geologic, and hydrologic phenomena controlling wetlands and wetland functions and communicate with climatologists, geologists, and hydrologists to achieve an optimal management program.

Chapter 2 begins by discussing systems, their fundamental components, and their dynamics. Landscapes and wetlands as interactive systems are then

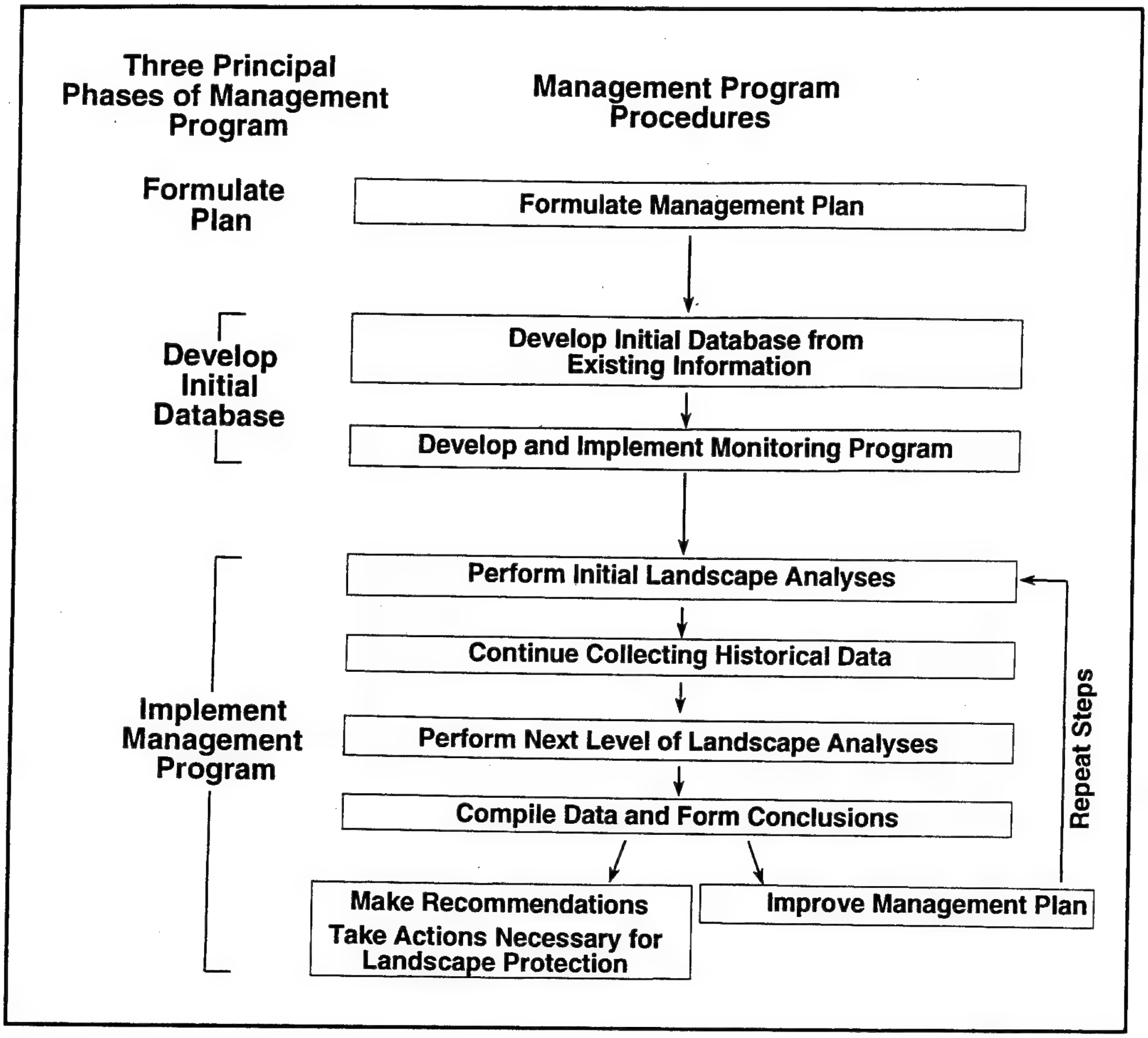


Figure 1. General framework for developing and implementing a wetland management program

described. Chapter 3 discusses potential earth resource information sources and geographic data management systems. Chapter 4 describes methods to characterize Earth's surficial features by land use/land cover classifications and by remote sensing imagery. Chapter 5 describes the role of meteorology, geology, and hydrology in landscape and wetland systems. Methods to monitor and evaluate landscape processes are also presented. Chapter 6 presents a detailed discussion of the framework for wetland systems management.

2 Landscapes and Wetlands as Systems

General Systems Considerations

Systems are structured sets of objects and/or attributes. These objects and attributes consist of components that: (a) are capable of assuming variable magnitudes and (b) exhibit discernible relationships with one another and operate together as a complex whole (Chorley and Kennedy 1971). Entities that show interdependence of components and unity of change are amenable to systems analysis.

There are several ways in which systems can be characterized. The most common division is based on system function in which isolated, closed, and open systems are recognized (Chorley and Kennedy 1971). Isolated systems have boundaries closed to import and export of both mass and energy. These occur more commonly in the laboratory than in nature. Closed systems have boundaries which prevent the import and export of mass, but not energy. The Earth and atmosphere together represent a closed system. Open systems are characterized by exchange of both mass and energy, with their surroundings. The components of these systems and the interrelationships between them tend to adjust so there is a steady input and output of materials and energy. The majority of natural systems are open.

The second major system classification is based upon their internal structure (Chorley and Kennedy 1971). There are a large number of structural system types (morphological, plants, animals, human social). To effectively manage wetlands in a landscape context, four types of these structural systems need be understood. These are, in order of increasing complexity, morphological, cascading, process-response, and control systems (Figure 2).

Morphological systems consist of individual system components and the network of structural relationships between them. Morphological systems are formal and structural properties integrated to form a recognizable operational part of physical reality (Chorley and Kennedy 1971). For example, morphological properties in a beach system include: slope, width, wave height, sediment size, etc.; the relationships between these parameters constitutes a morphological system (Figure 2a). Another example of a morphological system, which is discussed in Chapter 5, is drainage basin morphometry. An

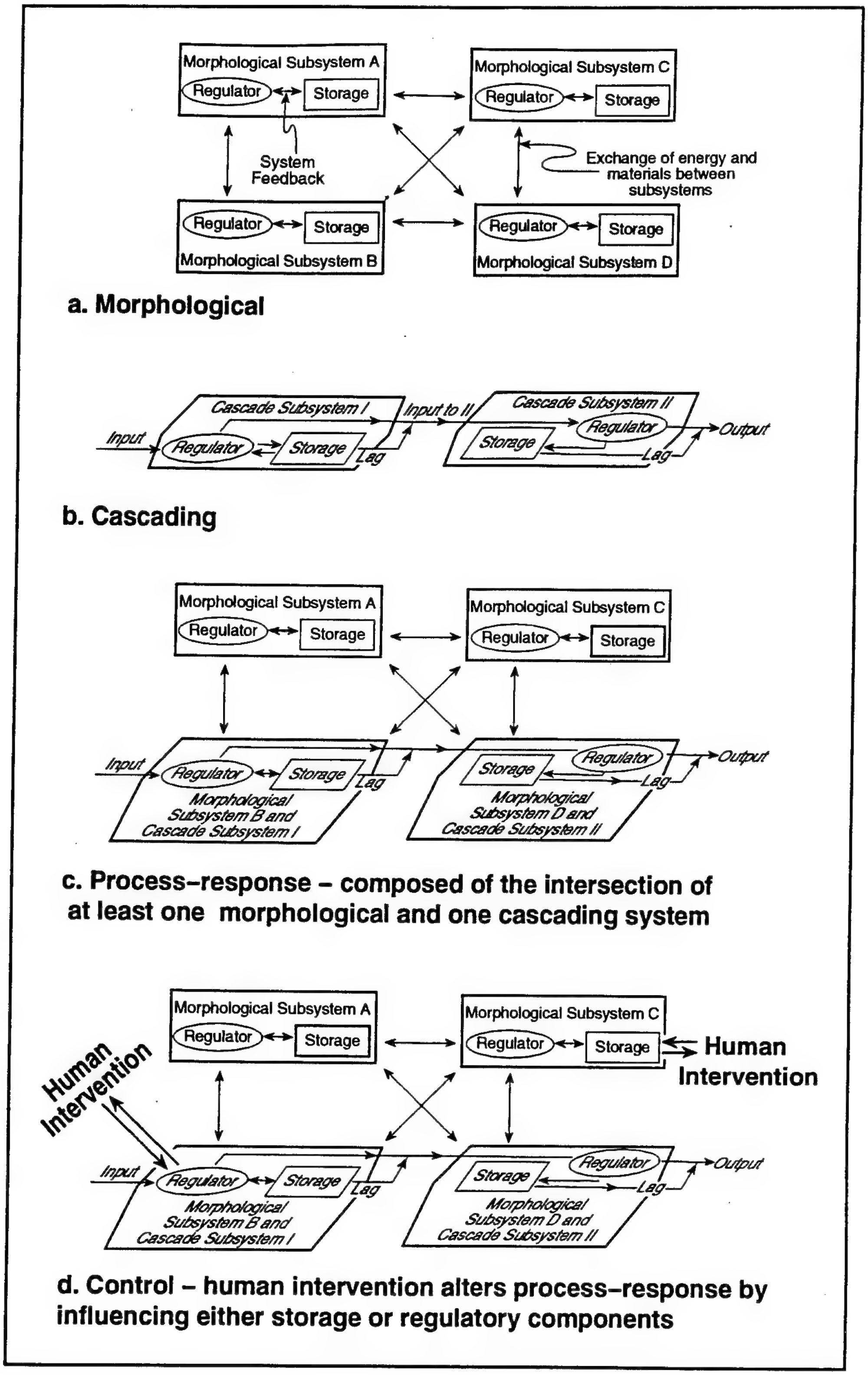


Figure 2. Types of systems that control landscape equilibrium and development. (After Chorley, Schumm, and Sugden (1985))

important feature of morphological systems is the role of feedback loops in which a portion of system output is rerouted as input for another phase of the operation, especially for self-correcting and control purposes (Chorley and Kennedy 1971).

Cascading systems are defined by the paths followed by mass and energy as they proceed through these systems. Cascading systems are chains of subsystems having both magnitude and geographical location, which are dynamically linked by a cascade of mass and energy (Figure 2b). In this cascade, mass and energy output from one subsystem becomes input for adjacent subsystems (Chorley and Kennedy 1971). Cascading systems in nature vary markedly in scale and magnitude, ranging from the global solar radiation cascade to the basin hydrologic cycle cascade, to a cascading system formed by a the flow of water and sediment through stream channels. Two essential components of system cascades are regulators and storage elements (Figure 2b). Regulators are components of systems that have the capacity to redirect the flow of mass or energy into storage, or from one subsystem to other subsystems. Storage components are capable of retaining portions of mass or energy for a period.

Process-response systems are composed of linkages of at least one morphological and one cascading system (Figure 2c), and relate form to process (Chorley and Kennedy 1971). Process-response systems are open and therefore depend upon external sources of energy and material. Those factors not defined as part of a system, but which affect system dynamics, are known as **external variables**. Changes in external variables induce mutual adjustments of morphological and cascading components (Howard 1968). Adjustments of systems to changes in inputs of energy and materials are known as **dynamic equilibrium**. Process-response systems, however, contain a certain degree of **inertia** (which is related to feedback loops) such that rapid fluctuations in external variables influence the system parameters as their average. Inertia in systems implies that process-response systems never fully reach equilibrium. Inertia may periodically induce conditions in which system components and dynamics no longer reflect the processes acting on them. Disparity between system process and response reach such a degree of instability that **threshold** conditions are reached, and systems adjust toward new equilibrium states. Having reached threshold conditions, the speed at which systems adjust toward the new equilibrium state is known as **recovery rate**.

In process-response systems, certain key variables, or regulators, can be conveniently modified to produce operational changes in the distribution of energy and mass within cascading systems, and thereby bring about changes in equilibrium relationships among the morphological variables linked to them (Chorley and Kennedy 1971). **Control systems** are process-response systems in which key components are manipulated by some intelligence (Figure 2d). These manipulations cause systems to operate in a manner suitable to the intelligence. Flood control dams are examples of drainage basin control systems. The control of mass and energy flow by a limited number of key components implies that the state of a system and its change through time can be assessed by monitoring and evaluating specific system parameters or

variables (**forcing functions**) that characterize a system's current composition, organization, and dynamics (Howard 1968). Characterizing parameters are selected for their utility in defining the current state, their relevance to systems dynamics, and their ease of measurement (Howard 1968). Although systems may be largely controlled by a limited number of external variables, it is important to realize that many forms and functions of systems arise from the complex interaction of several factors.

Landscapes and wetlands are comprised of interactive components that undergo a series of complex adjustments to change and are therefore most effectively managed as process-response systems. Treating landscapes and wetlands as process-response systems highlights the multivariate character of their forms and processes, yet implies that a limited number of factors control system equilibrium.

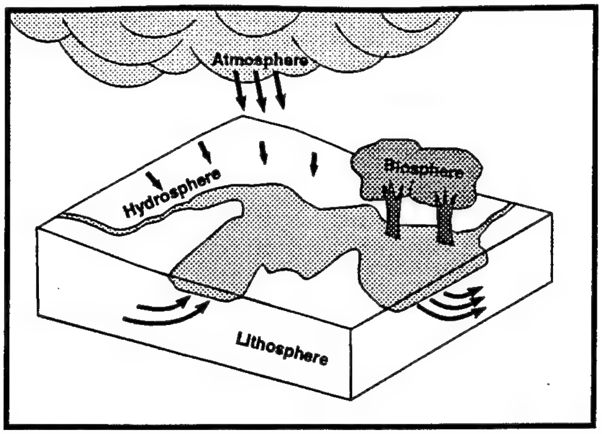
Landscapes as Systems

Landscape systems are aggregates of landforms and those materials and forces involved in topographic transformation. **Landforms** are any recognizable physical form or feature of the earth's surface having a characteristic shape. **Landscape processes** are actions produced when forces induce chemical or physical changes in materials or forms at the earth's surface. Or more simply, landscape processes are the means by which earth materials and forms are produced from something else (Ritter 1986).

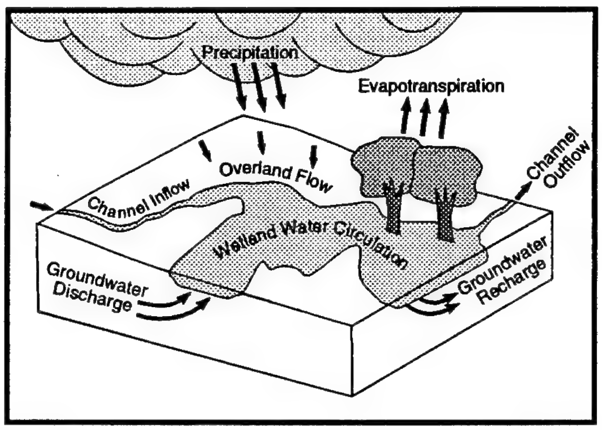
Landscape systems are products of interacting atmospheric, lithospheric, hydrospheric, and biospheric phenomena which transform and redistribute energy and materials in near surface environments (Figure 3). From an ecologic perspective, landscapes are composed of clusters of interacting ecosystems that are repeated in a similar form (Forman and Godron 1986). Landscapes are multidimensional in which processes occur above (climate), at (ecology, hydrology, geomorphology) and below (geology, soils, groundwater flow) the earth's surface. Like other complex process-response systems, landscapes are characterized by dynamic equilibrium, which is periodically punctuated by threshold conditions. Moreover, landscapes may be characterized by evaluating a limited number of processes which reflect the overall stability and dynamics of the system.

Drainage basins are viable process-response systems and are fundamental units for evaluating landscapes. **Drainage basins** (or **watersheds**) are areas that gather water from precipitation and deliver it to streams, lakes, wetlands, or oceans. They are areas delimited by drainage divides and occupied by drainage networks. Drainage basins range in size from less than 1 km^2 to the Mississippi River Basin which is a hierarchy of drainage subbasins which total more than 3 million km^2.

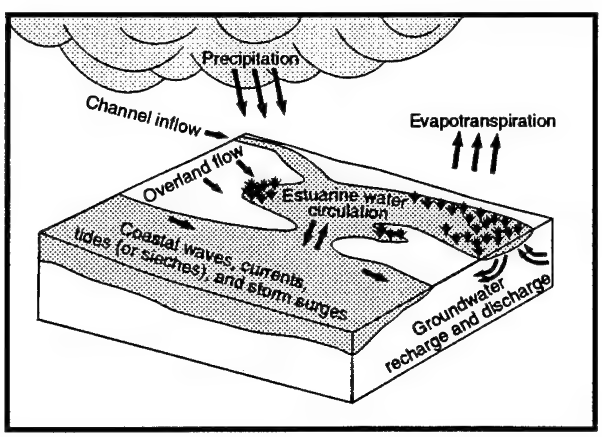
Choice of landscape area to be evaluated is of primary importance in wetland management because at different spatial scales, different variables



a. Interactions of atmosphere, lithosphere, hydrosphere, and biosphere to produce a landscape



b. Hydrologic components of a landscape that control wetland functions at inland settings



c. Hydrologic components of a landscape that control wetland landscapes at coastal settings

Figure 3. Major landscape phenomena

become dominant in determining landscape form and process (Chorley, Schumm, and Siegden 1985). A spatial classification is presented in Table 1 to provide a framework for understanding the scale of landscapes and wetlands in terms of other geographic features. This document is primarily concerned with fifth- and sixth-order spatial scales (Table 1).

Table 1
Spatial Ordering of Landforms[1]

Order	Examples
1st	Continents, oceans, tectonic plates
2nd	Physiographic provinces, mountain ranges, massifs, plateaus
3rd	Medium-scale geologic units such as folded sequences, fault blocks, volcanoes
4th	Large-scale erosional/depositional features such as large watersheds, major deltas, long continuous beaches
5th	Medium-scale erosional/depositional features such as flood plains, alluvial fans, cirques, moraines, large wetlands
6th	Small-scale erosional/depositional features such as small valleys, sand dunes, small watersheds
7th	Hill slopes, stretches of stream channels, wetlands
8th	Slope and flat facets, pools, riffles, wetland microtopographic features
9th	Stream and wetland bed forms, slope terracettes
10th	Microtopography associated with pebbles and sand grains

[1] After Chorley, Schumm, and Sugden (1985).

Significant changes in inputs, forms, processes, and outputs within landscapes occur over time (Figure 4). When evaluating landscape evolution, the time span considered is critical to understanding landform development process (Schumm and Lichty 1965), and distinction between time-span duration is essential to perception of equilibrium (Figure 5). **Steady time** transpires within brief intervals (days or months). Within the steady time interval, landforms do not change and therefore they are truly independent of time (Ritter 1986). **Graded time** occurs within a single to as much as several thousand years. Equilibrium in this interval incorporates changes in which offsetting effects tend to maintain a system at some constant average condition. **Cyclic time** transpires over thousands to perhaps millions of years. During time-spans of this order of magnitude, fluctuating conditions are not offsetting and fundamental changes to the system are taking place. Wetland management is primarily concerned with time intervals ranging from hours to decades (i.e., steady and graded time phenomena). However, longer time-scale phenomena acting on wetlands should be recognized. Equilibrium states, magnitude and frequency of natural disturbances, and evaluation of anthropogenic change on landscape systems are discussed further in Chapter 5.

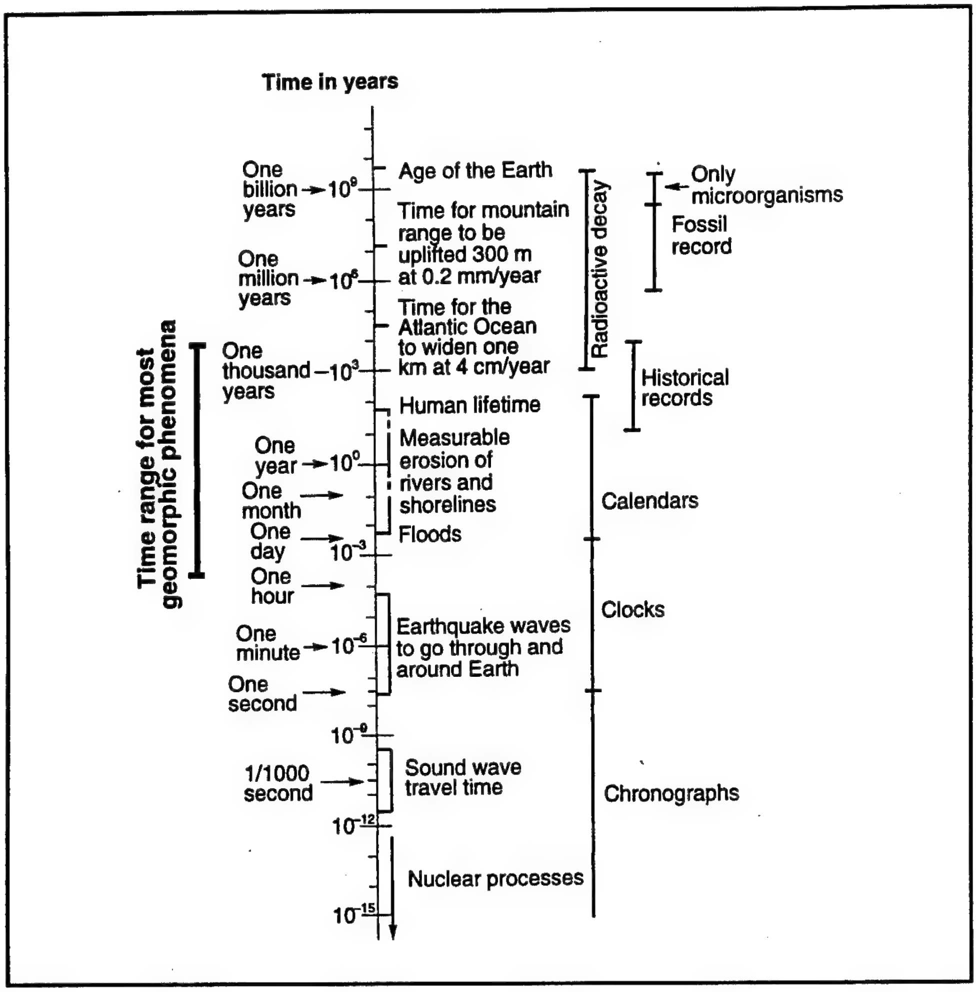


Figure 4. Orders of magnitude of duration for some common earth processes and events. To the left is the general time range for geomorphic phenomena. To the right are methods used to measure time. (After Press and Sevier (1986))

Wetlands as Systems

Wetlands are areas inundated or saturated by surface or groundwater at a frequency and duration sufficient to support and, that under normal circumstances, do support a prevalence of vegetation typically adapted for life in saturated soil conditions (U.S. Army Engineer Waterways Experiment Station (USAEWES) 1987). Wetlands are a valued resource because specific wetland functions are beneficial to the general public and the natural environment (Table 2). Wetland functions are primarily controlled by landscape hydrology (i.e., the principal cascading system). Principal components of the wetland hydrologic system are: surface inflow, groundwater discharge, precipitation, bidirectional surface flow induced by tides and sieches, wetland water circulation, evapotranspiration (ET), groundwater recharge, and surface water outflow (Figure 3; Table 3).

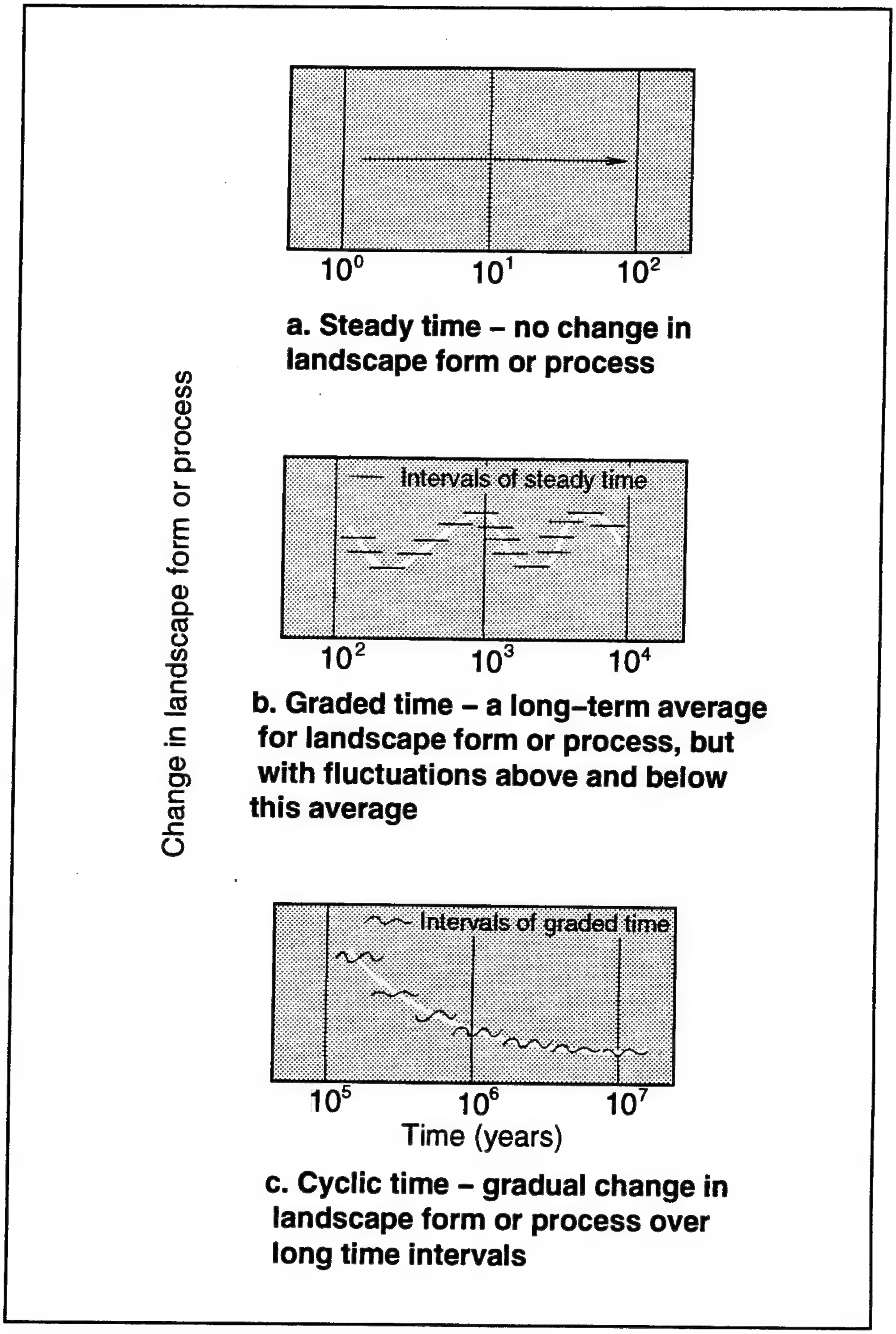


Figure 5. Different time intervals and associated equilibrium in geomorphic analysis. (After Schumm (1977))

Table 2
Functions of Wetlands and Their Value[1]

Wetlands Functions	Value of Wetland Functions
Groundwater recharge	Maintain groundwater aquifers
Groundwater discharge	Maintain baseflow for aquatic flora and fauna
Floodflow alteration	Reduce flood-related damage
Sediment stabilization	Minimize erosion loss and damage
Sediment/toxicant retention	Maintain or improve water quality
Nutrient removal/transformation	Maintain or improve water quality
Production export	Provide nutrition for downstream fish populations
Aquatic diversity/abundance	Maintain biodiversity Preserve threatened and endangered species
Wildlife diversity/abundance	Maintain biodiversity Preserve threatened and endangered species
Cultural activities	Provide recreational, educational, and research opportunities

[1] After Adamus et al. (1991) and Smith (1993).

Wetland equilibrium

Because wetlands are generally low relief landforms, subject to relatively wide variations in water levels, and are transitional between aquatic and terrestrial ecosystems, they are commonly **pulsed systems** (Odum 1984; Niering 1987); that is, they are subject to short-term, high-intensity events which commonly result in significant changes in their systems. Natural disturbances include fire, windstorm, ice storm, ice push, cryogenic soil movement, temperature fluctuations, precipitation variability, fluvial erosion and deposition, flooding, coastal erosion, dune migration, saltwater inundation, karst processes, and biotic disturbance. These natural disturbances may be an integral part of a wetland's role in the landscape system and visa versa. These disturbances serve to maintain heterogeneity of the landscape (White 1979; Reice 1994) and are the means by which landscape systems maintain long-term stability by resetting ecologic and geomorphic conditions to previous states. Because natural disturbances are an integral process in wetland landscapes, analysis of the magnitude, frequency, and timing of these phenomena is an essential element of wetland management (Chapter 5). Threshold conditions in landscapes and wetlands are commonly induced by human activities (Hooke 1994). Like atmospheric events, the relative impact of human activities also depend on the magnitude, frequency, and duration of perturbation. However, many human impacts, particularly land use change, tend to induce prolonged changes to material and energy inputs such that affected landscapes do not have sufficient time to reestablish equilibrium conditions before the next human alteration. Hence, human impacts on landscapes tend to be cumulative. Because wetlands typically serve as areas of concentration in the flow of

Table 3
Critical Parameters Associated with Hydrologic Components of a Landscape

Hydrologic Components	Critical Parameters
Surface water inflow (channelized flow)	Drainage basin size and shape
	Position of wetland in the drainage basin
	Water sources
	Chemistry
	Flow rates
	Types and amount of resistance to flow
	Annual and seasonal variability of flow rates
	Flow response to storms
	Volume of sediment transported
Surface water inflow (overland flow)	Area contributing overland flow to wetland
	Soil characteristics
	Land use
	Chemistry
	Possible nonpoint source pollution
	Flow response to storms
	Annual and seasonal variability
Surface water flow (tides)	Average tidal range
	Spring tidal range
	Neap tidal range
	Frequency and magnitude of storm surges
	Ebb and flow velocities
	Degree of interaction with groundwater
Groundwater discharge	Aquifer characteristics
	Relative contributions of local, intermediate, and regional groundwater flow systems
	Chemistry
	Annual and seasonal variability
Precipitation	Monthly rainfall totals
	Annual rainfall totals
	Annual and seasonal variability
	Timing, magnitude, and frequency of storms
	Snowfall totals

(Continued)

Table 3 (Concluded)	
Hydrologic Components	**Critical Parameters**
Wetland water circulation	Hydroperiod
	Hydrodynamics (flow direction and velocity)
	Water residence times
	Hydraulic connections (surface and subsurface)
	Water storage capacity
	Fetch
	Water chemistry
	Circulation patterns
	Response of flow and water levels to storms
	Amount of suspended sediment
Evapotranspiration	Monthly ET totals
	Annual ET totals
	Annual and seasonal variability
	Effect on wetland water chemistry
Groundwater recharge	Aquifer characteristics
	Relative contributions to local, intermediate, and regional groundwater flow systems
	Chemistry
	Annual and seasonal variability
Surface water outflow	Flow rates
	Annual and seasonal variability of flow rates
	Resistance to flow
	Flow response to storms
	Volume of sediment transported

materials and energy through landscape systems, they are especially vulnerable to cumulative impacts. Wetlands in disequilibrium may exhibit the following properties: (a) changes in species diversity, (b) reduced internal material cycling (i.e., feedback loops), (c) reversion of plant and animal community structure to earlier successional stages, (d) decline in efficiency of resource use, and (e) altered species interactions (Odum 1985; Leibowitz et al. 1992).

Wetlands as hydrogeomorphic systems

Landscape/wetland interactions are best understood by considering wetlands as hydrogeomorphic systems. The hydrogeomorphic characterization of wetlands has three basic criteria: (a) geomorphic setting, (b) water sources, and (c) hydrodynamics (Brinson 1993). The geomorphic setting includes the topographic location of the wetland within the landscape, and the

configuration of the wetland surface. Wetland water sources are: precipitation, surface water inflow, and groundwater discharge. Hydrodynamics refers to the direction and rate of water movement within a wetland.

Geomorphic setting. Geomorphic setting describes the wetland form and position within the landscape. Five principal geomorphic settings are recognized: depressional, extensive peatlands, riverine, fringe, and slope (Table 4). Each geomorphic setting tends to have a distinctive combination of hydroperiod, direction of flow, and zonation of vegetation (Brinson 1993).

Depressional wetlands include such landforms as kettles, potholes, vernal pools, and Carolina Bays. Because they commonly occur high in drainage basins, depressional wetlands are typically more dependent on atmospheric water exchanges than other wetland types. In climates where mean precipitation exceeds ET, depressional wetlands commonly accumulate peat which eventually leads to umbrotrophic conditions. If peat development and accumulation continue for a sufficient period, a wetland then becomes an extensive peatland.

Extensive peatlands cover large areas such that the peat substrate dominates movement and storage of subsurface water, mineral nutrition of plants, and the topography of the landscape (Moore and Bellamy 1974). Examples of extensive peatlands include blanket bogs and tussock tundra. As peatlands expand across the landscape, surface features develop which are not entirely dependent of the underlying topography. Bogs in higher topographic positions may become connected through unchannelized surface flow to peatlands lower in the drainage basin. Hence there is a gradient from headwater umbrotrophic wetlands with diffuse outlets to peatlands with distinct outlets and fen trophic levels.

Riverine (floodplain) wetlands form elongate landscape features. Examples of riverine wetlands includes oxbow lakes and bottomland hardwood forests. Hydroperiods tend to be brief and flashy in headwater streams and long and steady in high-order steams. As stream channel and floodplain gradients are reduced, the capacity of water to directly influence wetland geomorphology through accretion, erosion, and transport is diminished. In such cases, hydrology and vegetation interact to modify the substrate through bioaccumulation and, if the processes continue, a riverine wetland may be transformed into a depressional wetland or extensive peatland (Gosselink and Turner 1978; Brinson 1993).

Fringe wetlands occur in estuaries where tidal forces dominate or in lakes where winds and seiches influence shoreline hydrodynamics such that bidirectional surficial flow regimes predominate. Hydroperiods in fringe wetlands are long as the result of the cumulative frequency of flooding events, especially those affected by diurnal astronomic tides. Wetlands along lakes that are too small to develop frequent seiches are categorized as depressional.

Table 4
Hydrogeomorphic Classification of Wetlands and Frequently Associated Functions

Examples of Geomorphic Settings	Evidence	Commonly Associated Functions
Depressional Wetlands		
No apparent inlet or outlet: located on topographic high	Topographically isolated from other waterbodies; drydowns frequent; water levels below wetland ground surface much of the time.	Lack of inlet and outlet induces potential for groundwater recharge and discharge. Low water table induces potential for floodflow alteration. Topographic isolation induces potential for sediment/toxicant and nutrient retention and transformation. Topographic isolation tends to create unique physical and chemical environments which may induce potential for aquatic and wildlife diversity/ abundance.
Surface outlet only: located on topographic high	Drydowns frequent; water levels below wetland ground surface much of the time.	Lack of inlet induces potential for groundwater discharge. Low water table induces potential for floodflow alteration. Outlet induces potential for production export.
Located in marginally dry climate (e.g. prairie pothole region); variable inlets and outlets	Wide variations in water depth; water levels below wetland ground surface much of the time. Tends to retain flow.	Tendency to retain flow induces potential for groundwater recharge, floodflow alteration, and sediment/toxicant and nutrient retention and transformation. Generally wet environment in a marginally dry climate induces potential for aquatic and wildlife diversity/ abundance.
Both surface inlet and outlet: large catchment sustains marginal riverine features	Water budget dominated by surface flows or strong groundwater discharge; fresh and nutrient-rich water.	High flow rates induce potential for groundwater discharge, sediment stabilization, and production export. Position near rivers induces potential for floodflow alteration. Nutrient-rich waters induce potential for aquatic and hence wildlife diversity/ abundance.
Extensive Peatlands		
Peat layers form topographic high, isolating peatland surface from groundwater system	Peat substrate, saturated most of time. Plant species indicate ombrotrophic conditions; surface flow negligible. Low pH and nutrient content in water.	Position above groundwater table and saturated conditions induce potential for groundwater recharge. Position as topographic high induces potential for production export.
Peat layers may or may not form topographic high; peatland surface influenced by groundwater system	Peat substrate, saturated most of time. Plant species indicate minerotrophic conditions. Circumneutral pH and nutrient-rich water.	Connection with groundwater flow system induces potential for groundwater recharge and discharge, and nutrient retention/ transformation. Nutrient-rich waters induce potential for aquatic and hence wildlife abundance/diversity.
		(Sheet 1 of 3)

Table 4 (Continued)

Examples of Geomorphic Settings	Evidence	Commonly Associated Functions
Riverine (Floodplain) Wetlands		
Streamside zones of intermittent streams	Headwater locations of first order streams; flows not continuous.	Position high in watershed induces potential for groundwater recharge. Association with small watershed (relatively high floodflow peaks) and variable, noncontinuous flow induces potential for production export.
High gradient-downcutting	Bedrock-controlled, alluvium generally lacking.	High relief induces potential for groundwater discharge. Downcutting induces potential for production export. Scour normally precludes wetland development so that uniqueness of environment in the landscape induces potential for aquatic and wildlife diversity/abundance.
High gradient-accreting	Substrate controlled by fluvial processes; coarse substrate.	Coarse substrate and high relief of surrounding landscape induce potential for groundwater discharge. Fluvial processes induce potential for sediment stabilization. High gradients induce potential for production export. Rarity of these ecosystems in high gradient setting induces potential; for aquatic and wildlife diversity/abundance.
Medium gradient-accreting	Channelized flow; slope steep enough for meandering; evidence of oxbows, meander scrolls, etc. consistent with fluvial processes.	Generally continuous flow induces potential for groundwater discharge (baseflow). Periodic flooding induces potential for floodflow alteration, sediment stabilization and production export. Fluctuating water table levels induces potential for sediment/toxicant and nutrient retention/transformation. Fluvial processes create variations in topography which induce potential for floodflow alteration and aquatic and wildlife diversity/abundance.
Low-gradient alluvial: floodplain bottomland hardwood forest	As above, but in low-gradient form. High suspended sediment in streams.	Generally continuous flow induces potential for groundwater discharge (baseflow). Periodic flooding induces potential for floodflow alteration, sediment stabilization, and production export. Fluctuating water table levels, abundant plant structures, and high suspended load induce potential for sediment/toxicant and nutrient retention/transformation. Fluvial processes establish variation in topography which induces potential for floodflow alteration and aquatic and wildlife diversity/abundance.
Low-gradient nonalluvial (i.e., low in suspended sediments): Florida cypress strands and sloughs	Flows not channelized or channels shallow; Manning coefficient normally high.	Low gradient nonchannelized flow, and high Manning coefficients induce potential for groundwater recharge, floodflow alteration, sediment stabilization, and sediment/toxicant and nutrient retention/transformation.

(Sheet 2 of 3)

Table 4 (Concluded)

Examples of Geomorphic Settings	Evidence	Commonly Associated Functions
	Fringe Wetlands	
Shallow depressions or flats along marine coasts, with inlets and outlets, either directly or indirectly, connected to marine waters	Subject to astronomic tides, sea-level controlled.	Near constant movement of water induces potential for sediment stabilization, production export, and aquatic and wildlife diversity/abundance.
Shallow depressions or flats along lake shores with inlets, either directly or indirectly connected to open lake	Subject to seiches; lake-level controlled.	Near constant movement of water induces potential for sediment stabilization. Location along large fresh water body relatively high in the watershed induces potential for floodflow alteration. Location along large inland water bodies which serve as transit habitats along migration routes induces potential for aquatic and wildlife diversity/abundance.
	Slope Wetlands	
Located at break in slope; associated with intersection of unconfined aquifer and ground surface; no surface inlet, may or may not have outlet	Water generally nutrient-rich, chemistry similar to groundwater; little if any pooling of water although soils are continuously saturated by constant supply of groundwater.	Connection with groundwater flow system induces potential for groundwater recharge and discharge, and nutrient retention/transformation. Location on slope and near constant supply of water induces potential for production export. Nutrient-rich waters induce potential for aquatic and hence wildlife abundance/diversity.
Not located at break in slope; associated with intersection of perched aquifer and ground surface; no surface inlet, may or may not have surface outlet	Water generally nutrient-rich, chemistry similar to groundwater; little if any pooling of water although soils are continuously saturated by constant supply of groundwater.	Connection with groundwater flow system induces potential for groundwater recharge and discharge, and nutrient retention/transformation. Location on slope and near constant supply of water induces potential for production export. Nutrient-rich waters induce potential for aquatic and hence wildlife abundance/diversity.
Modified from Brinson (1993)		
		(Sheet 3 of 3)

Slope wetlands occur where the water table intersects a sloping ground surface and are generally associated with seeps and springs. Two principal slope wetland types are recognized: those associated with breaks in slope and those associated with perched water tables. Unidirectional flow predominates in slope wetlands, and although standing water is not characteristic, soils are commonly saturated year round.

Categorization of the geomorphic setting requires that wetlands be analyzed in a landscape context because a given wetland may have characteristics of more than one hydrogeomorphic type. For example, if isolated from overbank flow, an oxbow may behave more like a depressional wetland, even though a riverine process initiated its development.

Water sources. Hydrologic inputs to wetlands are: precipitation, groundwater discharge, and surface water inflow. Surface inflow includes flooding from tides, overbank flooding, channel flow, and overland flow. The quantity of water that each source contributes to the hydroperiod could be expressed as an annual average if a detailed water budget has been developed. Even if a comprehensive water budget has not been established, it may be possible to rank the relative importance of the sources to the total site water balance. Seasonal and annual variation should be considered. Techniques to evaluate wetland landscape hydrology and calculate water budgets are discussed in Chapter 5.

Once the water budget has been evaluated, the relative importance of the water sources can be related to specific wetland types (Figure 6). Wetlands in which precipitation dominates tend to be nutrient poor and are subject to drawdowns during the dry season (Figure 7). Wetlands in which surface water is the predominant source tend to be particularly sensitive to their position in the watershed and are characteristically high-energy systems (i.e, experience high rates of water flow with subsequent erosion and high-sediment transport rates). Wetlands in which groundwater is the predominant source tend to be nutrient rich and have relatively stable water levels.

Hydrodynamics. Hydrodynamics refers to the motion of water and the capacity of water to do work (i.e., transport sediment and nutrients, flush hypersaline water from sediment, transport nutrients to roots, erode, aerate sediment, etc.). Because of the stochastic nature of most hydrodynamic processes, the capacity or opportunity to perform work is seldom quantified. Hence, inferences regarding hydrodynamics are constrained to evaluation of velocity of flow, rate and duration of water table fluctuations, sediment size distribution, and capacity to replace soil moisture deficits created by ET.

Hydrodynamics can be simplified into three components: (a) vertical fluctuations of the water table that result from ET and subsequent replacement by precipitation or groundwater discharge; (b) unidirectional surface flow from relatively high-velocity channel to sluggish overland sheet flow; and (c) bidirectional surface or nearsurface flow associated with tides or seiches. These prevalent directions of water movement correspond to depressional and extensive peatland, riverine and slope, and fringe wetlands, respectively.

Although the hydrodynamics of all wetlands involve a vertical component, it occurs in its simplest form in depressional wetlands. The two major variables affecting vertical fluctuations are rate of ET and the frequency at which water deficits are replaced by groundwater and surface water inflow. Although organic substrate conditions in peatlands cause water movement to

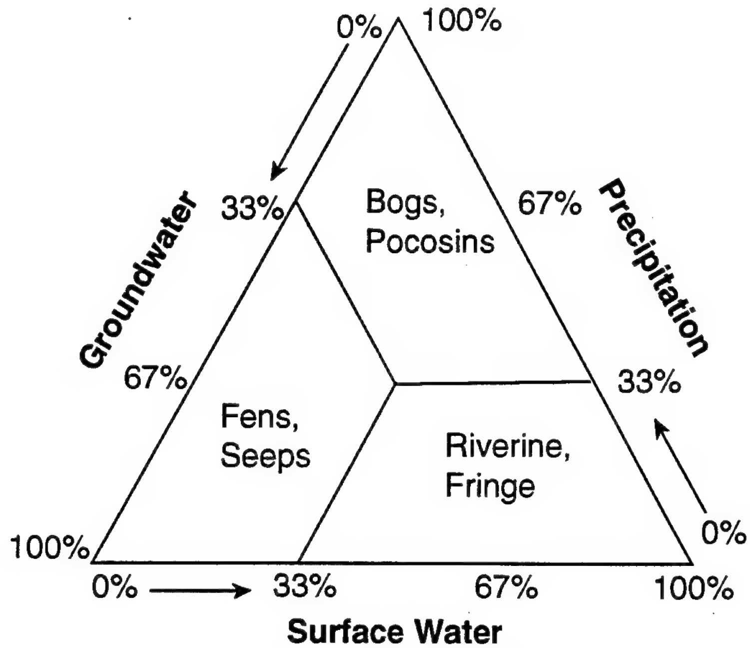


Figure 6. Relationship between the relative contribution of three water sources (precipitation, groundwater recharge, lateral surface flow) and major wetland types. (After Brinson (1993))

be complex, hydrodynamics in these wetlands are dominated by vertical fluctuations.

Unidirectional flow of water can range from barely perceptible surface and near-surface movement to high-velocity overbank discharge. Wetlands with unidirectional flow are very open systems and therefore long-term balance of input and output of materials and energy determines the stability of these wetland systems. Riverine wetlands are characteristically high-energy systems (at least seasonally) that are dominated by surface water inflow and outflow (Figure 7). Slope wetlands are low- to moderate-energy systems that are dominated by groundwater inflow and, if any, surface water outflow.

Average velocities of bidirectional tidal currents on wetland surfaces tend to be low, because the majority of flow is restricted to tidal channels. While any one tidal cycle is unlikely to have much influence on the flow of materials through the system, the cumulative effects of diurnal tides becomes a dominant force in these wetland systems. Bidirectional flow is generated either by astronomic tides, wind, or both. Both regular and irregular flooding is associated with astronomic tides, depending upon the position of the wetland relative to the open water and upland, and therefore these wetlands vary in their hydrologic energy levels (Figure 7). Regularly flooded wetlands are characterized by high productivity and intense biogeochemical activity. For lakeside wetlands, seiches are the source of water level fluctuations, and therefore

these wetlands are flooded less regularly than wetlands associated with astronomical tides.

Interaction Between Wetlands and Landscapes

Interactions between landscape and wetland systems are most readily understood by evaluating:

a. Rates of flow of energy and matter through a landscape.

b. How, where, and to what degree do changes in the rate of flow of energy and material occur.

c. How flow rate changes modify the energy/matter regime.

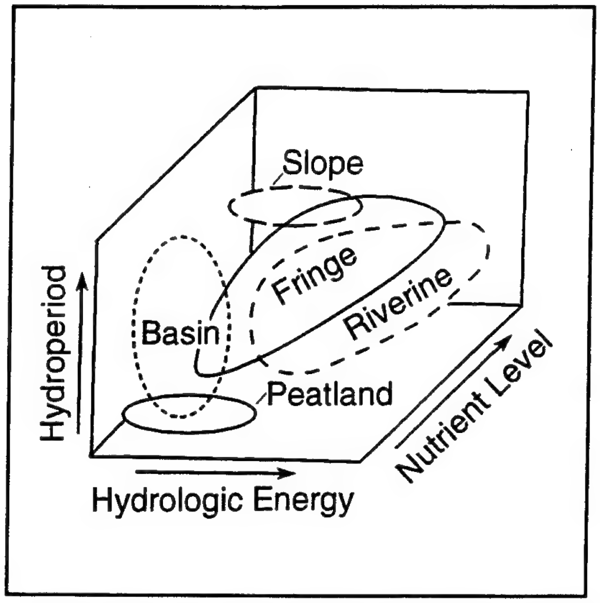


Figure 7. Relative ranges of hydroperiods, hydrologic energy, and nutrient levels of the five hydrogeomorphic wetland types. (After Brinson (1993))

This evaluation process is facilitated by considering interacting landscape and wetland systems as sources, sinks, transformers, amplifiers, resistors, capacitors, catalysts, and buffers (Table 5).

Wetland functions (Table 2) describe wetland processes that affect the landscape (and are beneficial to humans). These interactions are but a few of the myriad of wetland processes which influence landscapes. Because wetlands are open, process-response systems in which virtually all energy and material are supplied by the surrounding landscape, there are innumerable landscape processes and materials which affect wetland functions (Table 6). Hajic and Smith (in press) describe critical landscape processes for six of the wetland functions (groundwater recharge/discharge, floodflow alteration, sediment stabilization, sediment/toxicant retention, nutrient removal/transformation, and production export). Their work provides a conceptual framework and necessary information (in a GIS format) to evaluate regional-scale (second- and third-order spatial scale of Table 1) processes that influence wetlands.

With such a large number of interactions between landscapes and wetlands, it may seem impossible to characterize the flow of energy and material between them. Fortunately, as with systems in general, a few specific variables (forcing functions) characterize the spectrum of interactions between

landscapes and wetlands. Forcing functions for a particular wetland depend on the local climate, physiographic province, its hydrogeomorphic type, its position in the watershed, among many other factors. Chapter 5 describes principles and methods of hydrometeorology, geology, and hydrology which provide information necessary to identify and evaluate landscape and wetland forcing functions.

Table 5
Terminology to Characterize Wetland/Landscape and Landscape/Wetland Interactions

Type of Interaction	Definition	Wetland Interaction with Landscape	Landscape Interaction with Wetland
Source	Capable of generating materials or energy that are unique to that system and capable of exporting to other systems.	Production export function (Table 2)	Wetlands are open systems and the surrounding landscape serves as source for nearly all energy and matter
Sink	Capable of dispersing fluid energy in the course of a hydrodynamic process, or capable of long-term retention of material.	Sediment/toxicant retention function (Table 2)	Groundwater recharge
Transformer	Capable of converting energy and matter from one form to another.	Nutrient removal/ transformation function (Table 2)	Replenishment of nutrient-poor, oxygen-poor surface water effluent
Amplifier	Capable of increasing the intensity of a particular process or volume of a material.	Aquatic diversity/ abundance function (Table 2)	Increased sediment and nutrient loading by agricultural activity
Resistor	Capable of reducing the rate of flow of energy and materials.	Sediment stabilization function (Table 2)	Construction or roadways across lowland areas
Capacitor	Capable of temporarily storing energy and materials for later release at a modified rate.	Floodflow alteration function (Table 2)	Seepage of precipitation into upland soil and subsequent wetland groundwater discharge
Catalyst	Causes activity between objects or processes without itself being affected.	Extended residence times and anoxic conditions induce toxin uptake by plants and sediments	Agricultural runoff elevates phosphorus levels, producing algal blooms, anoxic conditions, and fish kills
Filter	Capable of removing specific constituent from the water or sediment.	Extended residence times and intense microbial activity converts organic nitrogen to mineral and atmospheric nitrogen	Urbanization increases runoff, peak flows, and chemical loading
Buffer	Minimizes interaction with other systems.	Shallow water, muddy substrate, and thick vegetation protects wetland wildlife	Urban expansion restricts the range of wetland wildlife

Table 6
Elements of the Landscape Which Most Influence Wetland Functions

Function	Landscape Materials and Processes which May Influence Wetland Function
Groundwater recharge	Magnitude-frequency-duration-timing of storm events; precipitation and evapotranspiration regime; percentage of time soil and substrate remain frozen; soil characteristics; substrate characteristics; tectonic lineaments and fractures; relative position in regional groundwater flow system; lowering of water table levels by groundwater pumping; position of wetland water surface relative to water table; ratio of shoreline length to wetland area; land use/land cover; topography.
Groundwater discharge	Precipitation and evapotranspiration regime; percentage of time soil and substrate remain frozen; soil characteristics; substrate characteristics; tectonic lineaments and fractures; relative position in regional groundwater flow system; lowering of water table levels by groundwater pumping; size and location of recharge areas; recharge rates; ratio of shoreline length to wetland area; land use/land cover; size of wetland relative to watershed; topography.
Floodflow alteration	Magnitude-frequency-duration-timing of storm events; snowfall amounts; soil characteristics; magnitude-frequency-duration-timing of flood events; upstream flood control structures; land use/land cover; size of wetland relative to watershed; watershed size; size of wetland constrictions; relative position of wetland in watershed; wetland gradient; topography; drainage basin morphometry; number; size and relative location of other wetlands in the watershed.
Sediment stabilization	Magnitude-frequency-duration-timing of storm events; wind regime; ratio of annual precipitation to evapotranspiration; soil characteristics; substrate characteristics; sediment input volume; tidal range; tidal characteristics; wave and marine current regime; streamflow rate and volume; fetch; nearby coastal engineering structures; upstream flood control structures; land use/land cover; position relative to the coastline; position in the watershed; topography.
Sediment/ toxicant retention	Temperature, wind, and precipitation regime; magnitude-frequency-duration-timing of storm events; soil characteristics; substrate characteristics; erosion and transport processes; sediment input volume; residence times; percentage of surface water outflow from wetland; land use/land cover; fetch; position in the watershed; wetland gradient; topography.
Nutrient removal/ transformation	Temperature, wind, and precipitation regime; magnitude-frequency-duration-timing of storm events; soil characteristics; erosion and transport processes; sediment input volume; sediment grain size; residence times; percentage of surface water outflow from wetland; land use/land cover; fetch; wetland gradient; position in the watershed; topography.
Production export	Temperature, wind, and precipitation regime; magnitude-frequency-duration-timing of storm events; magnitude-frequency-duration-timing of flood events; percentage of surface water and groundwater inflow; residence times; percentage of surface water outflow from wetland; position in the watershed; topography.
Aquatic diversity/ abundance	Timing, depth, and duration of wetland hydroperiod and changes over time; relative amount of surface and groundwater input; relative amount of water loss by evapotranspiration; residence times; land use/land cover; topography; proximity to similar ecosystems; continuity of similar ecosystems; size of wetland buffer.
Wildlife diversity/ abundance	Timing, depth, and duration of wetland hydroperiod and changes over time; residence times; land use/land cover; topography; proximity to similar ecosystems; continuity of similar ecosystems; size of wetland buffer.
Cultural activities	Land use/land cover; proximity to population centers; abundance and diversity of fauna and flora; accessibility.

3 Information Sources and Data Management Systems

Effective wetland management requires a fundamental understanding of earth processes which control landscape evolution, and specific information regarding the atmosphere, lithosphere, hydrosphere, biosphere, and human activity in and around wetlands. Information must be stored and processed in such a way as to highlight those landscape components and processes that are critical to wetlands and their functions. In this chapter, sources of available earth resource information and data management and analysis systems are discussed.

Sources of Preexisting Landscape Information

Effective wetland systems management requires extensive earth resource data (Table 7). A great deal of information has already been generated and compiled for many parts of the United States. Unfortunately, there is no straightforward procedure to identify available information. To expedite the data gathering process, three tables have been compiled: Table 8 is a general list of organizations which generate, organize, and disseminate earth resource data; Table 9 is a list of organizations with large-scale wetland programs; and Table 10 is a list of organizations or on-line computer systems that are designed for earth resource data management and retrieval. Familiarity with Tables 8 through 10 should not only save time in the data gathering process, it should ensure thoroughness of the background research and help identify information gaps. Tables 8 through 10 are by no means exhaustive; other Federal, state, county, municipal, and private organizations undoubtedly have generated and compiled relevant data and the reader is encouraged to seek them out. Other recent compilations of data sources relevant to wetland stewardship and management include World Wildlife Fund (1992), Leibowitz et al. (1992, Appendices D-E), and Lyon (1993, Appendix A). Hajic and Smith (in press) provides national-scale maps for many of the data coverages listed in Table 7; he also discusses which data coverages are relevant for assessment of specific wetland functions.

Table 7
Data Coverages Associated with Landscape Analysis

General Categories	Specific Coverages
General	Base map
	Population centers
	Transport routes
	Recreation areas
Land Use and Land Cover	Land cover
	Land use
	Land use and land cover change
	Buffers and pathways
	Remotely sensed imagery
Climate	Meteorologic instrument location map
	Temperature
	Precipitation
	Atmospheric water vapor
	Wind
	Pressure
	Solar radiation
	Evapotranspiration
	- Potential
	- Actual
	Atmospheric water budget
	Synoptic climate
Geology	Geologic data location map
	Subsidence/uplift rates
	Bedrock (prelate Pleistocene)
	- Composition
	- Structure
	- Lineaments
	Late Pleistocene - Holocene
	Soils
	- NRCS classification
	- Hydrologic soil group
	- Curve number
	Ongoing geologic processes
	- Weathering
	- Erosion
	- Transport
	- Storage
	- Sediment routing and budget

(Continued)

Table 7 (Concluded)	
General Categories	**Specific Coverages**
Geomorphology	Landform
	Equilibrium
	Frequency, magnitude, duration, timing of geomorphic events and threshold conditions
	Basin morphometry
Hydrology	Hydrologic instrument location map
	Groundwater
	- Prelate Pleistocene aquifers
	- Late Pleistocene - Holocene aquifers
	- Water table elevation
	- Potentiometric surface
	- Local, intermediate, and regional groundwater flow systems
	Surficial
	- Rivers and streams
	-- Rates and volumes
	-- Flood prone areas
	- Overland flow
	-- Rates and volumes
	-- Routing
	- Wetland
	-- Water level
	-- Water volume
	-- Residence time
Biology	Ecosystem types
	Animal communities
	Plant communities
	Threatened and endangered species locations and ranges
	Biomass density
	Emergent plant density
	Plant and animal species population densities

Table 8
Principal Organizations that Generate, Organize, and Distribute Earth Resource Information

Agency	Division or Program	Brief Description	Access
Bureau of Land Management (BLM)		BLM is responsible for managing the nation's public land (~272 million acres). The vast majority of this land is located in the West, although small scattered parcels are in the East. BLM has obtained aerial photographs over lands they manage. Their coverage is available through USDA-ASCA Aerial Photography Field Office (Table 10). Further details and a list of district, state, and field offices are available from the location cited to the right.	Bureau of Land Management 1849 C Street NW MIB 5600 Washington, DC 20240 202-208-5717
Ducks Unlimited (DU)		DU is the largest private-sector wetland conservation organization. DU is involved in wetland conservation projects in all fifty states as well as in Canada and Mexico. DU has been instrumental in the evolution of the North American Waterfowl Management Plan (NAWMP), an agreement between the U.S., Canada, and Mexico which establishes goals for rebuilding North America's waterfowl population. DU's Private Lands Programs encourages agricultural practices that enhance waterfowl habitats. The three regional DU offices are staffed by biologists who specialize in wildlife management.	Ducks Unlimited One Waterfowl Way Memphis, TN 38120-2351 901-758-3825
Forest Service		The U.S. Forest Service is in charge of the nation's forests and grasslands. They have collected aerial photography over and adjacent to national forests, and their holdings are available through EROS Data Center (Table 10). For much of the commercial forest land in the U.S., the Forest Service collects and maintains the Forestry Inventory and Analysis (FIA), a data base which records forest cover types/species, and monitors changes over time. Each region has a watershed management group which may be able to supply useful information. A list of the 10 regional offices can be obtained at the location cited to the right.	U.S. Forest Service 201 14th Street, SW Washington, DC 20250 202-205-1760
NASA	Earth Observing System (EOS)	NASA, other Federal agencies, and some foreign governments have developed plans to bring about clearer understanding of what is happening to the planet on a global scale. A major component of this international plan is the U.S. Global Change Research Program, of which NASA's Mission to Planet Earth (MTPE) is a major component. The most significant part of MTPE will be the Earth Observing System (EOS) whose headquarters is at the Goddard Space Flight Center. EOS will be a space-base satellite observation system that will collect long-term (15 year) data set to gain better understanding of the Earth's hydrologic and biogeochemical cycles, and climatic processes. The EOS Data and Information System (EOSDIS) will acquire, compile, process, and distribute EOS data. The first of six observation satellites is scheduled for 1998.	NASA Goddard Space Flight Center Greenbelt, MD 20771 301-286-8955
Nature Conservancy		The Nature Conservancy is the world's largest private, nonprofit owner of nature preserves with more than 6.5 million acres in holdings. In addition to purchasing of land, this organization carries out management and conservation research projects, and conducts wildlife inventories. Further details and a list of regional, state, and field offices are available from the location cited to the right.	Nature Conservancy 1815 North Lynn St. Arlington, VA 22209 703-841-5300

(Continued)

Table 8 (Concluded)

Agency	Division or Program	Brief Description	Access
Natural Resource Conservation Service (formerly Soil Conservation Service)		Local NRCS offices can supply soil maps and available soils data. Three digital soil data bases are becoming available: Soil Survey Geographic Data Base (SSURGO), State Soil Geographic Data Base (STATSGO), National Soil Geographic Data Base (NATSGO). These digital data base include interpretations of more than 25 physical and chemical properties for ~18,000 different soil series. Also included are data on flooding, subsidence, land use, etc. SSURGO is at scales ranging from 1:12,000 to 1:31,680, STATSGO is at 1:250,000, and NATSGO at 1:7,500,000. Further information is available from location cited at lower right. NRCS also has a series of wetland delineation maps (Table 9) associated with regulating the Food Security "Swampbuster" Act (1985). The NRCS also is responsible for collection and maintenance of the National Resources Inventory (NRI) in which change in the nation's agricultural lands, including wetlands, are monitored. A list of regional and state soil conservationist offices is available from location cited at upper right. World Wildlife Fund (1992, pp 265-268) also provides a list of state soil conservationist offices.	USDA Natural Resource Conservation Service Office of Public Affairs P.O. Box 2890 Washington, DC 20013 202-720-5157 Digital soil data are available at: National Soil Survey Center USDA NRCS Federal Building, Rm. 152 100 Centennial Mall, North Lincoln, NE 68508 402-437-5423
State Wetland Managers		Each state is involved in wetland management and protection. World Wildlife Fund (1992, pp 247-251) has compiled a list of contact persons.	
State Geological Surveys		Each state has an organization in charge of its natural resources and geology. A list of these organizations is available through the USGS Earth Science Information Center cited at right.	Reston ESIC 507 National Center Reston, VA 22092 800-USA-MAPS
USGS		The USGS is the nation's largest Earth science research agency. In addition, the USGS manages and disseminates a wide variety of Earth resource data (Table 10). A list of the regional, and other local offices is available from the location cited to the right. USGS Circular 900, "Guide to Obtaining USGS Information" (Dodd, Fuller, and Clark 1989) is inexpensive and useful for accessing geologic and hydrologic information available from the USGS.	Reston ESIC 507 National Center Reston, VA 22092 800-USA-MAPS
USGS	Water Resources Division (WRD)	In addition to being the nation's largest geologic research agency, the USGS WRD is also the largest hydrologic research and data management organization. A list of the WRP state offices is available from the location cited to the right. The annual WRD Information Guide, which may be obtained for free from the location cited to the right, is helpful for accessing hydrologic information of the USGS.	Reston ESIC 507 National Center Reston, VA 22092 800-USA-MAPS

Table 9
Principal Organizations and Programs that are Conducting Wetland-Related Research

Agency	Division or Program	Brief Description	Access
NOAA	National Coastal Wetlands Inventory (NCWI) and National Estuarine Inventory (NEI)	The NCWI is a comprehensive and consistently derived coastal wetland data base and is being generated to increase the knowledge of the distribution and areal extent of estuaries and improve understanding and management decisions. This information will be incorporated into the National Estuarine Inventory (NEI) and will be used in conjunction with other information such as land use, coastal pollution, and distribution of estuarine fishes and invertebrates to build a comprehensive digital (GIS) framework for evaluating the health and status of the nation's estuaries. This program uses a grid sampling method in which cells are approximately 45 acres. Analysis is adequate for national, regional, and estuary level analyses but not at the site specific level (Field et al. 1990).	Strategic Assessments Branch Ocean Assessment Division Office of Oceanography and Marine Assessment NOAA 11400 Rockville Pike Rockville, MD 20852 301-443-8843
NOAA	Coastwatch Change Analysis Project (C-CAP)	As part of the Coastal Ocean Program, NOAA is developing a comprehensive, standardized information system for monitoring land cover and habitat change in the coastal regions of the U.S. In this Federal and state interagency program, change is assessed using Landsat Thematic Mapper, other satellite sensors, and aerial photographs. Coastal wetlands and adjacent uplands will be mapped in coastal regions of the U.S. every 2 to 5 years to monitor change. This project is currently in the developmental stage, but has completed a survey of the Chesapeake Bay (Thomas and Ferguson 1990).	National Oceanographic Data Center User Services Branch NOAA/NESDIS 1825 Connecticut Ave., NW Washington, DC 20235 202-606-4549
NRCS	Wetland Inventory	Inland wetlands which have a high potential for conversion to cropland were identified. This program was implemented to ensure that agriculturalists conform with the wetland conservation provision of the Food Security "Swampbuster" Act (1985). Wetlands and converted wetlands are identified on a variety of maps and scales, but are usually recorded on photocopies of black and white photographs provided by the ASCS (Table 10). The inventory accounts for, more or less, all wetlands in a county or major land resource area (Teels 1990).	Natural Resource Conservation Service P.O. Box 2890 Washington, DC 20013 202-382-1839
USACE	Wetlands Research Program WRP	The WRP directly supports the Corps' mission to manage water resources and wetlands on millions of acres of land under Corps stewardship. The WRP, which began in FY 1991 and concluded in FY 1994, was administered at the U.S. Army Engineer Waterways Experiment Station (WES) Environmental Laboratory. WRP was organized into a four-pronged approach. Teams conducted research from the perspective of critical processes, delineation and evaluation, restoration and establishment, and stewardship and management of wetlands. In addition to producing a large number of reports, technical notes, journal articles, and other traditional technology transfer materials, products such as computer models and databases were also developed.	Wetlands Research and Technology Center U.S. Army Engineer Waterways Experiment Station CEWES-EP-W (TTS) Vicksburg, MS 39180-6199 601-634-4217

(Sheet 1 of 3)

Table 9 (Continued)

Agency	Division or Program	Brief Description	Access
USACE	Wetlands Research & Technology Center WRTC	The WRTC consolidates administrative, technological, and research skills available at WES. The Center facilitates and coordinates wetlands scientific and engineering work, wetlands training, inter-agency coordination efforts, and responds to anyone seeking answers to wetland related questions. Through the WRTC, experts in hydraulics, hydrology, chemistry, geology, physics, computer science, biology, forestry, archaeology, and many other fields, are available to solve wetland problems. WRTC supports a holistic, interdisciplinary approach to stewardship, management, restoration, and construction of wetlands.	Wetlands Research and Technology Center U.S. Army Engineer Waterways Experiment Station CEWES-EP-W (TTS) Vicksburg, MS 39180-6199 601-634-4217
USEPA	Wetland Mapping	EPA supports two types of wetland mapping activities: (1) for comprehensive planning under the Section 404 known as "advanced identification" (ADID) and (2) specific studies of 404 enforcement and Superfund sites. Using various types of remote sensing imagery, ADID projects assesses functions, values, and potential threats in areas of accelerating development. Mapping (scales 1:24,000 - 1:250,000) determines which wetlands are suitable and not suitable as fill disposal sites to better regulate development. Section 404 and Superfund mapping of specific sites (scales 1:3000 - 1:24,000) uses aerial photography and NWI maps (Maxted 1990).	Policy and Communications Staff Office of Wetlands, Oceans, and Watersheds USEPA 401 M Street SW Washington, DC 20460 202-260-9180
USEPA	Clean Lakes Program	This program supports activity from initial identification of potential water quality problems through postrestoration-monitoring. This program funds water quality assessment, diagnostic and feasibility studies, restoration and implementation projects, and postrestoration studies. More than 300 lakes have already been restored under this program.	Policy and Communications Staff Office of Wetlands, Oceans, and Watersheds USEPA 401 M Street SW Washington, DC 20460 202-260-9180
USEPA	Watershed Protection Approach	An integrated, strategy for protecting and restoring aquatic ecosystems and protecting human health (e.g. drinking water supplies and fish consumption). The approach focuses on the hydrologically defined drainage basins - watersheds - rather than on political boundaries. The approach has three cornerstones: (1) problem identification - identify threats to human and ecosystem health within the watershed; (2) stakeholder involvement - involve people most likely to be concerned or most able to take action; (3) integrated actions - take corrective actions in a comprehensive, integrated manner once solutions are determined.	Policy and Communications Staff Office of Wetlands, Oceans, and Watersheds USEPA 401 M Street SW Washington, DC 20460 202-260-9180

(Sheet 2 of 3)

Table 9 (Concluded)

Agency	Division or Program	Brief Description	Access
USEPA	Environmental Monitoring and Assessment Program (E-MAP)	Long-term program to monitor the nation's coastal waters, estuaries, forests, freshwater wetlands, surface waters, agrosystems, deserts, and rangelands. Monitoring involves both direct sampling and remote sensing analysis. Objectives of E-MAP include (1) estimation of the current status, extent, changes, and trends in indicators of the nation's ecological resources; (2) monitor indicators of pollutant exposure and habitat condition and seek associations between human-induced stresses and ecological condition; and (3) provide periodic statistical summaries and interpretive reports on the ecological status and trends to resource managers and the public. To accomplish these objectives, this program is researching environmental statistics, ecological indicators, landscape ecology, and ecologic risk characterization (Paul et al. 1990).	Office of Modeling, Monitoring Systems, and Quality Assurance USEPA (RD-680) 401 M Street, SW Washington, DC 20460 202-260-5780
USFWS	Coastal Barrier Resource System Mapping Program	The Coastal Barrier Resources Act (1982) established a 452,834-acre system of undeveloped, unprotected coastal barriers along 666 miles of the Atlantic Ocean and Gulf of Mexico. The USFWS National Wetlands Research Center has compiled a digital data base of the 1982 Coastal Barrier Resources System to monitor shoreline change and habitat loss. These maps are to be updated at least every five years (Watzin 1990).	USFWS National Wetlands Research Center 700 Cajundome Blvd. Lafayette, LA 70506 318-266-8500
USFWS	National Wetland Inventory	Wetlands types (classification of Cowardin et al. 1979) are being mapped throughout the U.S. Maps are available superimposed on 1:24,000 topographic base, or as mylar overlays. To date >68 percent of contiguous U.S. is mapped. NWI map distributors are located in each state and a list of these distributors is available through regional ESIC's (Wilen 1990).	ESIC 507 National Center Reston, VA 22092 800-USA-MAPS
USFWS	National Wetlands Research Center	The Center provides national leadership in research and development activities associated with protecting, restoring, and managing wetlands. Research focuses on wetland ecology, migratory birds, and technology development. At present, the Center is most active in the South, but has projects along the Atlantic and Pacific coasts.	USFWS National Wetlands Research Center 700 Cajundome Blvd. Lafayette, LA 70506 318-266-8500

(Sheet 3 of 3)

Table 10
Principal Organizations that Provide Earth Resource Data Management and Retrieval Services

Info. Type[1]	Agency	Division or Program	Brief Description	Access
A	NOAA	National Climatic Data Center (NCDC) and Environmental Technology Application Center	The NCDC stores and disseminates digital meteorological information on precipitation, wind, temperature, humidity, solar radiation, and evaporation. Regional centers may have data bases not archived at NCDC. DoD employees can obtain climatic data at no charge through the Air Force Air Weather Service at the Environmental Technology Application Center which is located at NCDC.	Environmental Technology Application Center Federal Building Asheville, NC 28801 704-271-4218
A, E, G, LU	NOAA	Environmental Service Data Directory	This is an on-line computer search system which accesses databases of the NOAA's National Climatic, Geophysical, and Oceanographic Data Centers. This system will soon be supplemented with Wide Area Information Service (WAIS) which will be more flexible in terms of key word searches. Personnel at NOAA Environmental Data Service Directory can help access other data directories. A background in computing, especially networking, is helpful in accessing data through this system.	NOAA Environmental Services Data Directory NOAA/EIS Ex2 1825 Connecticut Av., NW Washington, DC 20235 202-606-5012
E, H, LU	Defense Mapping Agency (DMA)	Distribution Center	The DMA compiles and distributes topographic (including considerable land use information), hydrographic, bathymetric maps, and aerial photographs. An account is necessary to request catalogues of these data. To open or verify an account, the Systems Integration and Management Activity Office (717-267-8156) should be contacted to get a Department of Defense Activity Code (DODAC). The DODAC is the account number that will be requested by DMA for ordering catalogues. To get your DODAC, your district's Unit Identification Code must be given.	Defense Mapping Agency Combat Support Center Attn: PMSR 6001 MacArthur Blvd. Bethesda, MD 20816-5001 301-227-2495
E, H, LU,	American Society for Photogrammetry and Remote Sensing (ASPRS)		A directory of more than 200 companies that produce and sell remotely sensed data is available from ASPRS for a small fee. The directory includes a 300 word description of each company.	American Society for Photogrammetry and Remote Sensing 5410 Grosvenor Lane Bethesda, MD 20814 301-493-0290

(Sheet 1 of 5)

Table 10 (Continued)

Info. Type[1]	Agency	Division or Program	Brief Description	Access
E,H, LU	EPA	Environmental Photographic Interpretation Center (EPIC)	EPIC provides a range of remote sensing and aerial photographic analyses, mainly in support of investigations under Superfund and other remediation activities. In support of the Clean Water Act, EPIC provides photo interpretations of wetlands including classification and delineation. EPIC acquires historical photography dating to the late 1930's from a range of Federal, state and local government agencies, and private aerial survey companies. Customized surveys to suit the requestor's needs as to scale, imagery type, time of year, are available through a network of private aerial companies across the country. Additional aerial information for use by EPIC includes USGS, Sanborn Fire Insurance Maps, and USDA Soil Survey photographs.	Environmental Monitoring Systems Laboratory P.O. Box 15027 Las Vegas, NV 89114 702-798-2525
E, H, LU	Library of Congress	Prints and Photographs Division	The Library of Congress maintains a large collection of historical photographs, some of which are aerial photographs dating from 1900-1940's. The Library will perform searches for mail inquiries to determine availability and cost of reproduction.	Library of Congress Prints and Photographs Division James Madison Memorial Building 101 Independence Av, SE Washington, DC 20540 202-707-6277
E, H, LU	National Archives and Record Service (NARS)	Cartographic and Architectural Branch (CAB) and Still Picture Branch (SPB)	Most aerial photographs of the U.S. taken for Federal agencies have been assembled at CAB. These photographs cover approximately 80 percent of the land area of the conterminous U.S. CAB also maintains a collection of military photographs of the U.S. from 1940's to 1960's. The National Archives will search a request and provide a price list of available prints.	National Archives 8th & Pennsylvania Av, NW Washington, DC 20408 703-756-6700
E, H, LU	USDA-Agricultural Stabilization and Conserv. Service (ASCA)	Aerial Photography Field Office	The field office archives and distributes photographs acquired from other agencies including Forest Service, NRCS, ASCS, and Bureau of Land Management. Their data contains photography from the National Aerial Photography Program (NAPP; 1:40,000 scale) and the National High Altitude Program (NHAP; 1:60,000 scale).	Aerial Photography Field Office USDA-ASCS P.O. Box 30010 Salt Lake City, UT 84130 801-975-3503

(Sheet 2 of 5)

Table 10 (Continued)

Info. Type[1]	Agency	Division or Program	Brief Description	Access
E, H, LU	USFWS	Wetland Values Database (WVD)	A computer repository and search system of earth science and natural resource information designed to provide bibliographic citations for literature pertinent to wetland values and functions. Currently there are nearly 15,000 records in the database. Each record contains a number of fields which can be searched for relevant information. These include, among others: author, year of publication, location, USACE District zones, USGS hydrologic unit number, ecoregion codes, land-surface form, and subject keywords.	Wetland Values Database USFWS/NWI 9720 Executive Center Drive, Suite 101 St. Petersburg, FL 33702- 813-893-3865
E, H, LU	USGS	Earth Resources Observation Systems (EROS) Data Center (EDC)	EROS is a data management system, systems development, and research center. The center houses the nation's largest collection of space and aircraft acquired imagery. The center is also a clearinghouse for information concerning holdings of foreign Landsat ground reception stations and satellite data acquired by other countries. EROS data base includes Landsat imagery, Advanced Very High Resolution Radiometers (AVHRR), National High Altitude Photography (NHAP) program, and National Aerial Photography Program (NAPP). Data from EROS is also accessible through the Earth Science Information Centers.	Costumer Services EROS Data Center Sioux Falls, SD 57198 605-594-6151
G, H, LU	USGS	Earth Science Data Directory (ESDD)	A computer repository and search system of earth science and natural resource information designed to provide bibliographic citations for literature pertaining to geologic, hydrologic, cartographic, and biologic sciences. ESDD is available for free and can be accessed from any computer equipped with a modem and telecommunications software. In addition, ESDD is available commercially on CD ROM.	ESDD Project Manager USGS 801 National Center Reston, VA 22092 703-648-7112

(Sheet 3 of 5)

Table 10 (Continued)

Info. Type[1]	Agency	Division or Program	Brief Description	Access
G, H, LU	USGS	Earth Science Information Center (ESIC)	Nationwide information and sales service for USGS maps and earth science publications. Using computerized information retrieval systems, ESIC also provides information about earth science materials from many public and private organizations. NWI maps are available through ESIC. Digital Elevation Models (which can, among other things, provide slope information) and Digital Line Graphs (vectorized topographic maps) are available through ESIC for GIS analysis. A list of the 12 regional ESID's is available from the location cited at the right. In addition, there are ESIC offices in all states (contact regional ESIC for listing). It is recommended that regional ESIC's be used for as a starting point for search and acquisition of maps, data, and other relevant information. However, this is a general source of information so that it is imperative that experts in local, state, and regional (SCS, WRD, EPA) offices be contacted to ensure access to all relevant current and historic data-bases.	ESIC 507 National Center Reston, VA 22092 800-USA-MAPS
H, LU	Federal Emergency Management Agency (FEMA)		FEMA distributes floodplain maps for about 22,000 communities throughout the U.S. Scales range from 1:24000 to 1:2400. Digitized versions of the maps are beginning to become available. A list of regional, state, and local offices are available at the location cited to the right.	Flood Map Distribution Center Federal Emergency Management Agency 6930 San Tomas Road Baltimore, MD 21227-6227 800-333-1363
H	NOAA	National Ocean Service Tidal Analysis Branch	Tidal data available include tide observation station locations, tidal heights, (6 minute and hourly intervals), times and heights of high and low water, monthly mean summaries, water temperature, and salinity.	NOAA National Ocean Service Tidal Analysis Branch 6001 Executive Blvd. Rockville, MD 20852 301-443-8311

(Sheet 4 of 5)

Table 10 (Concluded)

Info. Type[1]	Agency	Division or Program	Brief Description	Access
H	USGS	National Water Information Clearinghouse	The Clearinghouse disseminates all types of water-resource information. This organization is not a data repository but rather operates as a referral center to USGS, other federal, and state information systems. In addition, the Clearinghouse provides referral services to experts for specific hydrologic problems. Eventually the Clearinghouse will be decentralized with centers located across the country.	National Water Information Clearinghouse USGS 423 National Center Reston, VA 22092 800-H2O-9000
H	USGS	National Water Data Exchange (NAWDEX) and National Water Information System II (NWIS II)	NAWDEX currently serves as the Nation's center for water data storage and exchange. NAWDEX maintains three principal databases: STORET, WATSTORE, and the Master Water Data Index. Further details of the contents of these data bases is available from location at the right. NAWDEX services are available through a nationwide network of 60 assistance centers. A list of these assistance centers is available through the NAWDEX Program Office. NWIS II will soon be replacing NAWDEX. NWIS represents a further integrated of water chemistry, biological surveys, streamflows, well and aquifer characteristics, water use, sediment surveys, land use attributes and other spatial information collected and compiled by the USGS and other federal and state agencies. Data will be available in both table and GIS format. Although a national program, NWIS II will be available at state Water Resource Division offices.	National Water Data Exchange USGS 421 National Center Reston, VA 22092 703-648-6848
LU	U.S. Dept. Commerce Bureau of Census	Census of Agriculture	The Census compiles agriculturally related data every 5 years and publishes it for the Nation and for each state. In the 1987 census, each state publication has compiled statistics for such things as land use, total acreage of farmland, and types of agricultural chemicals used for each county, and how these statistics compare with the previous (1982) census.	Agricultural Division Bureau of the Census Washington, DC 20233 301-763-1113
LU	U.S. Dept. Commerce Bureau of Census	Topologically Integrated Geographic Encoding and Referencing System (TIGERS)	TIGERS is a GIS product of the Bureau of Census that contains all digital data from the 1990 census. The data base includes census geographic features (rivers, roads, lakes), feature names, demographic information, and their topologic relationships. Digital map data are available on a county basis at a scale of 1:100,000.	Data User Service Division Bureau of Census Washington, DC 20233-8300 301-763-5720

[1] The information types in column 1 are: A = atmospheric, E = ecologic, G = geologic, H = hydrologic, and LU = land use/land cover.

(Sheet 5 of 5)

Geographic Information Systems

Wetland systems management involves compilation and analysis of large amounts of spatial data. To create an environment in which timely and accurate management decisions can be made, information must be organized in systems that facilitate data synthesis and have the capability to analyze and compare many data layers simultaneously. A **Geographic Information System (GIS)** is an organized collection of computer hardware and software, geographic data, and personnel designed to efficiently collect, store, update, manipulate, analyze, and display geographically referenced information (Environmental Systems Research Institute 1992). A GIS can be thought of as a high-order map that has the capability of distilling information from two or more map layers (Star and Estes 1990).

Like maps, a GIS is concerned with two fundamental aspects of reality: position and attributes of locations. The position identifies precisely where a location is in two- or three-dimensional (2-D, 3-D) space. Attributes at a location are some qualitative or quantitative description such as amount of precipitation, land cover, or soil type. From a series of location and attribute information, which are all related to a common coordinate system (georeferenced), a variety of metric and topologic properties and relationships may be identified, including distance, direction, and connectivity. **Topology** defines the spatial relationships between the various objects and areas in a GIS. One of the distinguishing features of a GIS is that it has explicit mechanisms to store topology.

There are five essential steps in the development of a GIS: data acquisition, preprocessing, management, manipulation and analysis, and product generation (Figure 8). Data acquisition is the process of identifying and gathering relevant data (Tables 8 through 10). One must be careful not to underestimate the cost (time, personnel, and money) of the data acquisition phase. A GIS product is only as good as the thoroughness, accuracy, and precision of the underlying data sets. Often too little is known about the quality and resolution of preexisting data bases. Data quality assessment is discussed further in Chapter 6.

Data preprocessing involves manipulating information so that it may be entered into the GIS. Data format conversion most commonly involves extracting information from preexisting maps, photos, and printed records (stream gages, precipitation, etc.), and recording it in the computer data base. This part of the procedure typically involves digitizing data, and is often costly and time consuming. Preexisting digitized data may need to be converted into a format compatible with the GIS to be used. The second key preprocessing task is to establish a consistent methodology for specifying locations of objects in the data sets. This involves the identification of key locations (control points) common to all data coverages. The control points are the means by which all map coverages are spatially related (georeferenced) to each other.

Data management functions govern the creation of and access to the database itself. These functions provide consistent standards for data entry, updates, deletions, and retrieval. Data manipulation and analysis are the focus of the attention of the user in the GIS system. It is unlikely that wetland managers would be directly involved in the technical aspects of preprocessing of data, but would be thoroughly involved in examination and comparison of data layers, and derivation of new layers from preexisting coverages.

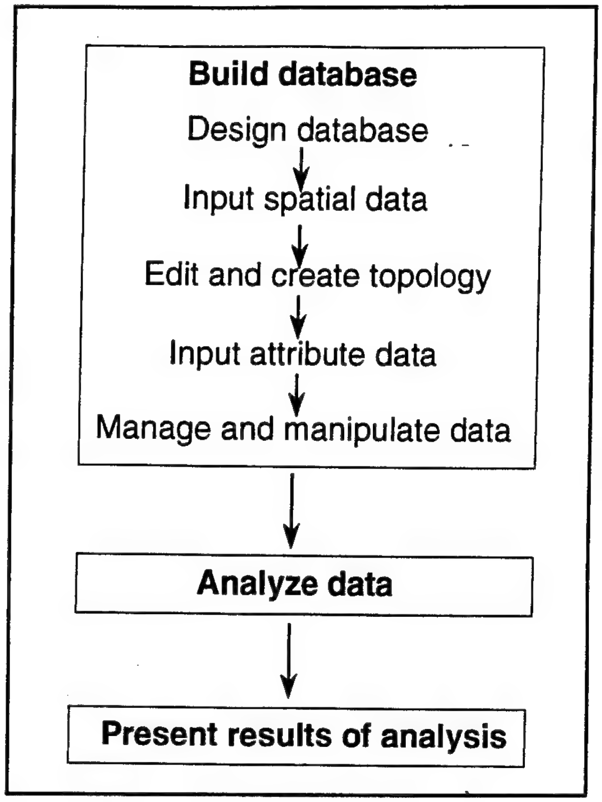


Figure 8. Flow chart summarizing essential steps in GIS analysis

The last fundamental element of a GIS is product generation. Final products should highlight processes that control wetland functions that are to be maintained or enhanced, or that control the equilibrium state of the wetland landscape. Effective final products should be simple, direct, and cartographically correct.

The capabilities of a GIS are determined by its capacity to supply analysts with sufficient information to answer questions concerning the geographic patterns recorded in the data. Queries take place through image display, coverage overlays, and logical overlays. Image display permits the analyst to present a specified data set on the display screen, and to manipulate such things as colors, scales, and other qualities as desired. Overlay capabilities permit the analyst to superimpose two or more coverages so that multiple patterns can be seen together. Logical overlays permit the analyst to define a new set of variables or categories based upon matching different overlays. For wetland managers, primary goals of GIS analysis are to identify those processes that are critical to wetland functions and the equilibrium state of the landscape and to predict changes in input of energy and matter induced by land use changes.

There are several GIS software packages available. Vector-based software packages include ARCINFO™ and Intergraph™. Raster-based software includes ERDAS™ and GRASS. The International GIS Source Book (GIS World Inc. 1993), which is published annually, is an extensive reference and guide to available GIS software, technology, and services.

4 Earth Surface Features

Land Use and Land Cover

Land use and land cover have a profound influence on soil development, erosion rates, and hydrology within a landscape. Because land use and land cover changes are probably the major factor currently altering wetland landscapes, they merit special attention. Most land use and land cover studies are based on satellite images and aerial photographs with reconnaissance fieldwork. This procedure offers the fastest, most economical way to compile earth surface information. Because human activity has and continues to modify large segments of landscapes, land use and land cover information should be updated regularly, and changes monitored.

Land use and land cover maps can be compiled from information provided by the Forest Service, the Department of Agriculture, and the U.S. Geological Survey (USGS) (Tables 8 through 10). The USGS has compiled digital land use/land cover maps for various parts of the United States; at scales of 1:250,000 and 1:100,000, these maps are of limited use for analyses of individual watersheds. Some states, counties, and municipalities have compiled or are compiling land use/land cover maps.

Land cover is distinct from land use (Dobson 1993). Land cover is material whereas land use is the product of laws, customs, and activities. For example, a deciduous forest may be a managed wildlife reserve, unmanaged private land, national forest, timber plantation, private hunting area, or an area proposed for development. The different uses of such a forest would have markedly different impacts on a nearby wetland site. Thus, land use and land cover should be mapped separately.

Land cover

Because of differing research goals and scales of analysis, there is not a universal classification for land cover. The classification scheme presented here is a slightly modified version of Norton, Organ, and Litwin (1985) which is an expanded version of Cowardin et al. (1979) wetland classification system. The Norton, Organ, Litwin (1985) classification system (Table 11) is presented here because it was designed with wetland management in mind.

Table 11
Land Cover Classification System

UV – Unvegetated Uplands
1. Bedrock
2. Rubble
3. Cobble/gravel
4. Sand
5. Silt/clay

HU – Herbaceous Uplands
1. Graminoid
2. Herb/forb
3. Mixed

EM – Emergent Vegetation
1. Persistent
2. Nonpersistent
3. Narrow–leaved nonpersistent
4. Broad–leaved nonpersistent
5. Narrow–leaved persistent
6. Broad–leaved persistent

SS – Scrub/Shrub
1. Broad–leaved deciduous
2. Needle–leaved deciduous
3. Broad–leaved evergreen
4. Needle–leaved evergreen
5. Dead
6. Deciduous
7. Evergreen

FL – Flat
1. Cobble/gravel
2. Sand
3. Mud
4. Organic
5. Vegetated pioneer
6. Vegetated nonpioneer

SB – Stream Bottom
1. Cobble/gravel
2. Sand
3. Mud
4. Organic

RB – Rock Bottom
1. Bedrock
2. Rubble

AB – Aquatic Bed
1. Algal
2. Aquatic moss
3. Rooted vascular
4. Floating vascular

BB – Beach/Bar
1. Cobble/gravel
2. Sand

RF – Reef
1. Coral
2. Mollusk
3. Worm

RS – Rocky Shore
1. Bedrock
2. Rubble

FO – Forest
1. Broad–leaved deciduous
2. Needle–leaved deciduous
3. Broad–leaved evergreen
4. Needle–leaved evergreen
5. Dead
6. Deciduous
7. Evergreen
8. Plantation

UB – Unconsolidated Bottom
1. Cobble/gravel
2. Sand
3. Mud
4. Organic

DU – Dune/Swale Complex
1. Unvegetated primary dune
2. Primary dune–pioneer vegetation
3. Primary dune–herbaceous
4. Primary dune–woody
5. Unvegetated secondary dune complex
6. Secondary dune–pioneer
7. Secondary dune–herbaceous
8. Secondary dune–woody

ML– Moss/Lichen
1. Moss
2. Lichen
3. Mixed

US – Unconsolidated Shore
1. Cobble/gravel
2. Sand
3. Mud
4. Organic
5. Vegetated pioneer

DL – Developed Land
1. Low–density residential
2. High–density residential
3. Commercial
4. Industrial
5. Recreation and public
6. Nonstructure facilities, roads
7. Mining
8. Cemeteries
9. Abandoned–pioneer vegetation
10. Other

AG – Agricultural /Horticultural Land
1. Grain crops
2. Vegetable row crops
3. Orchard/vineyard
4. Inactive/bare
5. Cover crop
6. Livestock and specialty farms
7. Tree nursury
8. Horticultural gardens

OW – Open Water/Unknown Bottom

After Norton et al. (1985).

However, it can be modified, according to the level of detail sought, uniqueness of the study area, and goals of analysis. It is of note that this classification scheme, to some degree, mixes land use and land cover.

Other potentially useful land use/land cover classification schemes include Anderson et al. (1976), currently the most widely used land cover classification scheme in the United States. This system has the advantage of being open-ended which gives it flexibility in developing more detailed subclasses according to the user's needs. The Klemas et al. (1993) land cover classification system is oriented toward coastal areas. It was designed for NOAA to support management of fisheries habitats and living marine resources. Yet another hydraulically oriented land use system that emphasizes runoff-infiltration characteristics of the earth's surface is presented in Table 12, and will be discussed in more detail in Chapter 5.

Land cover delineation generally involves a combination of photogrammetric mapping and fieldwork. After aerial photographs are obtained, it is customary to visit the area for preliminary field reconnaissance. Initial visits

Table 12
Runoff Curve Numbers for Selected Agricultural, Suburban, and Urban Land Uses

Land Use	Hydrologic Soil Group A	B	C	D	Portion of Land Use in Watershed	Partial CN	Composite CN
	CNs for AMC I/II/III						
Cultivated land	42/62/79	52/71/86	60/78/90	64/81/92			
Pasture or rangeland: poor condition	48/68/84	62/79/91	72/86/94	76/89/96			
good condition	21/39/59	41/61/78	55/74/88	63/80/91			
Meadow	15/30/50	38/58/76	52/71/86	60/78/90			
Forest: thin stand, poor cover, no mulch	26/45/65	46/66/82	59/77/89	67/83/93			
good cover	12/25/43	35/55/74	51/70/85	59/77/89			
Open space, lawns, parks, golf courses, cemeteries etc.							
good condition: grass covers >75% of the area	21/39/59	41/61/78	55/74/88	63/80/91			
poor condition: grass covers < 75% of area	30/49/69	50/69/84	62/79/91	68/84/93			
Commercial and business areas (85% impervious)	76/89/96	81/92/97	85/94/98	87/95/98			
Industrial districts (72% impervious)	64/81/92	85/94/98	80/9197	83/93/98			
Residential							
Average lot size — Average % impervious							
<1/8 acre — 65	59/77/89	70/85/94	78/90/96	81/92/97			
1/4 acre — 38	41/61/78	57/75/88	67/83/93	73/87/95			
1/3 acre — 30	37/57/75	53/72/86	64/81/92	72/86/94			
1/2 acre — 25	34/54/73	51/70/85	63/80/91	70/85/94			
1 acre — 20	31/51/70	48/68/84	62/79/91	68/84/93			
Streets, roads, and parking lots:							
paved with curbs and storm drains	94/98/99	94/98/99	94/98/99	94/98/99			
gravel	58/76/89	70/85/94	76/89/96	80/91/97			
dirt	53/72/86	66/82/92	73/87/95	76/89/96			

To calculate the composite curve number (CN): determine the various land uses, hydrologic soil groups, and antecedent runoff conditions (ARC) present in the landscape; assign a CN for each soil class–condition; determine the proportion of the landscape that is occupied by each soil class–condition; multiply this proportion times the corresponding CN for each soil class–condition; and add these products.

After Mather (1978); Simon, Stoerzer, and Watson (1987); SCS (1985).

serve to clarify general vegetation patterns prior to airphoto analysis and to evaluate the land cover classification system (Norton, Organ, and Litwin 1985). Next, land cover classes are mapped from the airphotos on mylar or digital overlays. After thorough editing, the maps are then field checked.

Land use

Determination of land use involves expansion of the Developed (DL) and Agricultural/Horticultural (AG) Land classification (Table 11) over areas that appear unaltered by humans. There also is no universal land use classification scheme because of broad variations in local customs and unique types and scales of land alterations. Land use classes will also be modified according to the level of detail sought and the uniqueness of the study area. Land cover mapping not only involves remote sensing analysis, but also extensive site visits, interviews with local residents and local officials, and perusal of county

records. If possible, land use delineation should include a property ownership layer. Because ownership records generally extend back at least 100 years, assessing ownership trends is an indirect method to monitor land use over time.

Remotely Sensed Imagery

Plants, soils, bedrock, water, and human activity have distinctive reflective characteristics that can be used to identify their presence and condition by remote sensing. **Remotely sensed images** are graphic representations of areas and are typically produced by optical electronic devices. Common examples include multispectral imagery (MSI) from satellite platforms and aerial photographs from aircraft. The use of remotely sensed data has been identified as a major component of the Corps of Engineers Mission to Planet Earth (MTPE) Program. Table 13 lists the United States and foreign remote sensing

Table 13
A Listing of Commercial and Government Imaging Systems, Both U.S. and Foreign, for Use in Wetland Landscape Systems Management

NASA Earth Probes	
TRMM	Tropical Rainfall Measuring Mission
NASA MTPE Instruments	
ASTER	Advanced Spaceborne Thermal Emission and Reflection Radiometer
EOS SAR	Earth Observation System Synthetic Aperture Radar
GLRS	Geoscience Laser Ranging System
HIRIS	High-Resolution Imaging Spectrometer
MISR	Multi-Angle Imaging Spectro-Radiometer
MODIS-N	Moderate-Resolution Imaging Spectrometer-Nadir
Foreign MTPE Instruments	
ASAR	Advanced Synthetic Aperture Radar (The Netherlands)
AVNIR	Advanced Visible and Near-Infrared Radiometer (Japan)
E-LIDAR	Experimental Light Detecting and Ranging Radar (Japan)
IMB	Investigator of Micro-Biosphere (Japan)
Non-MTPE Instrument Useful for Landscape Analysis	
ERS-1 (SAR)	Synthetic Aperture Radar
JERS-1 (SAR)	Synthetic Aperture Radar
JERS-1 (SWIR)	Short Wavelength Infrared Radiometer
JERS-1 (VNIR)	Visible and Near-Infrared Radar
LANDSAT 7 (ETM)	Enhanced Thematic Mapper
NOAA (AVHRR)	Advanced Very High-Resolution Radiometer
RADARSAT (SAR)	Synthetic Aperture Radar
SPOT 4/5 (HRVIS)	High-Resolution Visual Imaging System

instruments identified for civil and nontactical military MTPE applications and imaging systems that will be available in the near future.

Remotely sensed images provide a valuable record of season-to-season and year-to-year variability in landscape conditions (Lyon 1993). Land cover analysis from remote sensing imagery requires a working knowledge of physical geography, geology, pedology, ecology, and plant biology. A remote sensing analyst must have site specific information regarding seasonal water level variations, growth cycles of plants including time of reproduction, growth rates, timing of onset of senescence, and preferred habitat.

Remotely sensed images are valuable historical documents. Aerial photographs have been taken across the United States by various Federal agencies since 1935 so that it is not uncommon to have at least 10 sets of aerial photographs taken at different times for a given site (Lyon 1993). With a series of aerial photographs, linkage of past changes in land use/land cover or major climatic events to changes in geomorphic forms and processes is possible. Aerial photographs may provide a means to evaluate recovery rates from intense storm events and to distinguish decadal-scale trends.

Color and infrared images reveal more information about plant and water resources than do black and white photographs. Color infrared images are particularly useful for identifying plant communities and for determining edges of the water surfaces by contrasting the very high absorption characteristics of water with the high reflectivity of soil. Further information on the use of remotely sensed data in landscape analysis is available in Barrett and Curtis (1982) and Cracknell and Hayes (1991).

Sources of aerial photographs include the USGS (EROS, ESIC), USDA-ASCA, EPA (EPIC), NOAA, NARS, ASPRS as well as many private companies (Table 10). In most counties, recent aerial photographs are on file at Natural Resource Conservation Service (NRCS; formerly Soil Conservation Service) offices. Photographs are commonly available through the state DOT, Department of Natural Resources, and other state, county, and municipal offices. A list of private companies selling preexisting or custom photographs is available through ASPRS (Table 10). Most topographic maps are compiled and updated from aerial photographs; these photographs can be obtained from the company that mapped the site. Information regarding companies that compile topographic maps is available through the ESIC (Table 10). Software packages such as ERDAS™ or PCI™ can be used to process remotely sensed images in such a way as to subdivide landscapes based on spectral characteristics of surficial features (ERDAS Inc. 1991). These spectral signatures can then correlated to land use, land cover, or geologic characteristics of the area.

5 Earth Materials and Processes

Landscapes are the product of interaction among the atmosphere, lithosphere, hydrosphere, and biosphere (Figure 3). Effective wetland management is engendered by a general understanding of these earth sciences and specific knowledge of monitoring and evaluating landscape components and processes. To accomplish these two broad goals, this chapter describes climatologic, geologic, and hydrologic principles and methods.

Climatology

Because wetlands are low relief landforms which are transitional between aquatic and terrestrial ecosystems, slight shifts in meteorologic trends can have significant impacts on wetlands and wetland functions. There are wetlands in which the contribution of surfacewater and groundwater components are minimal, but there are very few wetlands in which atmospheric components, precipitation and ET in particular, are not forcing functions.

Meteorology deals with the atmospheric phase of the hydrologic cycle and is defined as the science of atmospheric phenomena (Wiesner 1970). **Weather** is defined as the sum total of all atmospheric phenomena at a given time and place. **Climate** is the collective state of the atmosphere at a given place within a specific period of time. **Hydrometeorology** applies meteorologic data and methods to hydrologic problems. **Hydroclimatology** evaluates large-scale atmospheric interactions by monitoring and modeling of long-term climatic fluctuations and determining the influence of these changes on water resource systems.

Because of the highly fluid nature of air, and because of large-scale changes in the Earth's tilt during the course of the year, weather is stochastic (random) and deterministic (controlled by a myriad of antecedent conditions). The stochastic nature of weather requires intensive measurement of meteorologic components both spatially and temporally to adequately characterize climate of an area.

This section on climate discusses major sources of climatic information. It reviews the principal atmospheric components: solar radiation, temperature, precipitation, humidity, wind, pressure, and ET, and the techniques and instruments with which to measure them. The section then briefly describes synoptic climatology, which monitors decadal-scale climatic variations and trends and its application to wetland systems management.

Climatic data sources

Hourly and daily climatologic data are published by NOAA/National Weather Service (NWS) in the Climatic Data and Hourly Precipitation Reports. These reports, which are widely available at research libraries, show the locations of weather observation sites in each state. Meteorological data are available from over 11,000 NWS cooperative weather monitoring stations across the United States (NOAA 1989). Information regarding nearby cooperative weather stations, and access to data generated by them, can be obtained from the National Climatic Data Center (NCDC). NCDC data are available free to Department of Defense personnel through Naval Oceanography Command Attachment, located at NCDC. Details on climatologic measurements and instrumentation are presented in NOAA (1989). The National Water Summary 1988-1989 (Paulson et al. 1990) provides a succinct account of atmospheric moisture sources and general climatology for each state.

The Corps of Engineers and other Federal agencies collect real-time weather data. The majority of data used by the Corps is collected and archived by the NWS and transmitted to the Corps by the Automated Field Operational System (AFOS). Atmospheric data acquisition and monitoring by the Corps is such that >26,000 pieces of weather information are transferred between the Corps and NWS on calm days; much more data are transferred on days of extreme weather (Wingerd and Tseng 1991). In addition, other Federal and state agencies make field surveys after major storms to collect rainfall data caught in buckets, water troughs, and other open containers. Many local farmers keep rainfall data as do newspaper offices, television stations, banks, and municipal offices.

There are several atlases available which summarize weather data for the United States, including the national atlas (USGS 1970); climatic atlas (Environmental Science Service Administration 1968); water atlas (Geraghty et al. 1973); water encyclopedia (van der Leeden Troise, and Todd 1990); water balance atlas (Korzoun et al. 1977); rainfall magnitude-frequency atlases (Hershfield 1961; Miller 1964; Niedringhaus 1971, 1973; Frederick, Myers, and Auciello 1977; Wexler 1991); and evaporation atlas (Farnsworth, Thompson, and Peck 1982). The NWS is currently compiling updated rainfall magnitude-duration-frequency maps for the United States on a regional and seasonal basis.

Some maps from various climatic atlases are presented in the discussion below. Because meteorologic conditions vary over short distances, these

summary maps should only be used as conceptual guides, not for site specific water and energy budget calculations.

Atmospheric components

As in any system, the atmosphere may be subdivided into a series of interacting components. Principal meteorologic components include solar radiation, temperature, precipitation, humidity, wind, pressure, and ET. The components are interrelated such that motions and processes of the atmosphere are explained in terms of changes in pressure, temperature, and humidity which are brought about by variations in absorption of solar radiation at or near the earth's surface. To evaluate interactions among the atmosphere, landscapes, and wetlands, each of the atmospheric components, methods, and instruments to measure them are described.

Solar radiation. Radiation is the means by which solar energy is transferred to the earth's atmosphere and surface. Radiation is the ultimate source of energy for nearly all landscape processes (tectonic energy being the only other major source). Solar radiation is absorbed and reradiated unevenly by the lower atmosphere, hydrosphere, and lithosphere which create complex thermal gradients that induce atmospheric and oceanic circulation and produce climatic regions. At a landscape level, the intensity and duration of solar radiation determine temperature, ET, and the wind regime.

Solar radiation is the transmission of energy in the form of short electromagnetic waves (visible light, ultraviolet, X-ray, infrared, radio waves). Electromagnetic waves are screened during passage through the ionosphere (from $\sim$400 to 50 km above the Earth's surface) so that by the time they reach the stratosphere (from $\sim$50 to 7 km), 99 percent of the energy is within the 0.17-4 micron (μ) range (visible light is within the range 0.4-0.7 μ). Approximately 11 percent of the solar radiation intercepted by the Earth's atmosphere is used to vaporize water (Figure 9) with no change in temperature (latent heat of vaporization). This heat is later liberated to the surrounding atmosphere as water vapor condenses to form clouds and precipitation. Reflected solar radiation (atmospheric and terrestrial) is known as albedo and varies according to atmospheric vapor content (cloudiness) and surficial conditions (Table 14). Changes in cloud cover, content of atmosphere, or ground cover influence the routing of solar radiation which in turn strongly effects the hydrologic cycle and other earth processes.

Absorption of solar radiation raises the temperature of the earth's surface and atmosphere. The distribution of the temperature at the earth's surface is complex, however solar energy is absorbed such that surface and shallow subsurface temperatures approach an average of 21°C (70°F). The Earth radiates this absorbed energy as long-wave electromagnetic waves in the range 4-80 μ.

Solar radiation is measured with a variety of instruments including radiometers, actinometers, pyroheliometers, pyrradiometers, and pyrogeometers.

Solar radiation is generally measured in langleys (calories of radiation received per cm^2 per day). Incoming short wave radiation can be measured by shielding the under side of a radiometer. Long wave terrestrial radiation, although difficult to measure accurately, can be measured by shielding the upper side of a radiometer. Net radiation, which is solar minus terrestrial radiation, is measured if neither side of the radiometer is shielded. Total (or global) radiation is most commonly measured, though it is measured at a very limited number of sites around the United States Empirical equations, which are based upon parameters such as the number of sunshine hours per day and daily temperatures, are commonly used to evaluate solar radiation (Wiesner 1970). Solar radiation estimates, in turn, are used in various equations for estimating ET.

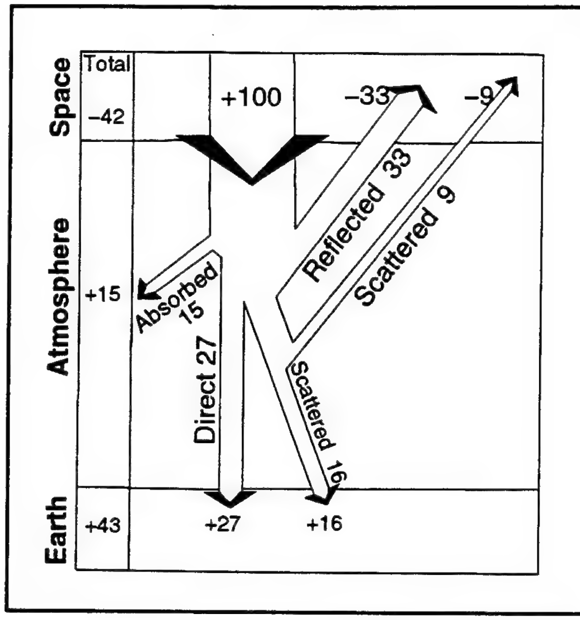


Figure 9. Generalized distribution of solar radiation

Table 14
Albedo for Different Types of Earth Surfaces

Material	Percent Reflected
Fresh snow	80-95
Old snow	50-60
Thick cloud	70-80
Thin cloud	20-30
Water (sun near horizon)	50-80
Water (sun near zenith)	3-5
Asphalt	5-10
Light soil	25-45
Dark soil	5-15
Dry soil	20-25
Wet soil	15-25
Deciduous forest	15-20
Coniferous forest	10-15
Crops	10-25

After Avery and Berlin (1992).

Temperature. In most regions of the United States, temperatures vary markedly with season. In fact many northern states experience significant periods of freezing temperatures during which time wetland functions are slowed, commonly to the point of suspended animation. The **growing season** is defined as the portion of the year during which, in 5 out of 10 years, the temperature remains above -2°C (28°F). Information regarding the dates on which the local growing seasons begin and terminate are available at NRCS offices.

Temperature, a function of kinetic energy, can be determined by measuring the physical properties of various materials, particularly their tendency to expand with increasing temperature. Mercury in-glass thermometers are commonly used and the readings are referred to as dry-bulb temperatures (see discussion of atmospheric moisture for description of wet-bulb temperature). Maximum-minimum thermometer sets, which must be read and reset manually, have been the most common method for recording daily ambient temperature (Brakensiek, Osborn, and Rawls 1979; NOAA 1989). Thermographs are used to automatically collect continuous temperature data over time. Satisfactory temperature readings are attained by circulating air at a given height (about 1 to 1.25 m) past a thermometer which is shielded from extraneous influences such as direct solar radiation. A thermometer screen, or instrument shelter minimizes radiant heat while allowing air to move freely past instruments in the shelter. A common type of thermometer shelter is the Stevenson screen which is a wooden cabinet, painted white, with a double floor and roof, and louvered sides which permit air currents, approximately 1 to 1.5 m/sec under normal conditions, to circulate through it.

Sling psychrometers are reliable, portable instruments for measuring temperature. They should be kept out of direct sunlight. Psychrometers are slung for a period of up to 2 min to reach free air temperature (USGS 1977; Brackensiek, Osborn, and Rawls 1979; NOAA 1989).

Precipitation. The amount of precipitation on a landscape is dependent upon the quantity of water vapor delivered to a region. In the United States there are three dominant moisture pathways which originate from three distinct air-mass source regions: (a) the Pacific Ocean, (b) the Atlantic Ocean and Gulf of Mexico, and (c) the Arctic region (see Hirschboeck 1988 and 1991 for more detailed discussions). As water vapor is delivered to a region, release of moisture from the atmosphere requires an uplift mechanism to cool (by adiabatic expansion) vapor to below its condensation temperature which induces cloud development and precipitation. There are four principal lifting mechanisms which cause precipitation: (a) thermal convection of moist, unstable air; (b) large-scale frontal convergence of contrasting air masses such that warmer, moister air is forced to rise over a cooler, drier air; (c) forced vertical motion in response to disturbances in the upper atmosphere; and (d) orographic uplift, which is the forced ascent of air currents up and over topographic barriers (Hirschboeck 1991). Convectional uplift tends to be of limited aerial extent but can result in intense precipitation. Frontal convergence affects extensive areas. Upper atmosphere disturbances can be either local or widespread, depending on the scale of the perturbation. Orographic

uplift can have local or widespread effects depending on the orientation and extent of topographic barriers relative to the prevailing wind directions (see Wiesner 1970 and Hirschboeck 1991 for more detailed discussions).

The Earth's troposphere (extending from ~ 7 km above to the Earth surface) may be broadly subdivided into two categories: baroclinic and barotrophic. The fundamental mechanisms of rain production of the baroclinic atmosphere are fronts and convergence of air masses. Thermal convection is the primary mechanism of rain production of the barotrophic atmosphere. Baroclinic conditions are characterized by widespread precipitation of moderate intensity and long duration, whereas barotrophic conditions are characterized by localized rainfalls of high intensity and brief duration. During the winter, most of the United States is controlled by baroclinic conditions. However, during summer most of the United States is controlled by barotrophic conditions. Hayden (1988) and Hajic and Smith (in press) provide more details and maps concerning baroclinic and barotrophic atmospheres and their areal and temporal distribution.

Precipitation over a landscape either falls directly on the landscape surface, is intercepted by vegetation, or reaches the surface via stemflow (transport of precipitation to the ground surface along plant stems and branches). Of the total precipitation on a wetland, generally two-thirds either evaporates directly or is intercepted by vegetation and is transpired back to the atmosphere (Foxworthy and Moody 1986). These proportions vary markedly with region, wetland type, and season.

Equally important as daily and monthly rainfall data to wetland systems management is information regarding the intensity, duration, and timing of precipitation events. Intense storms can erode, transport, and deposit large volumes of sediment and thereby cause significant changes in landscape forms and processes. Figure 10 shows the depth distribution of a 6-hr rainfall with the probability of being exceeded at least once every 50 years. What impacts would such a rainfall have on a wetland landscape? Would any thresholds be reached? How long would it take the landscape to recover to an equilibrium state? Analysis of recurrence intervals of intense storms, and their impact on landscapes is discussed further in this chapter in the section entitled Geomorphology.

Rain gages may be recording or nonrecording. Nonrecording gages account for total rainfall only and do not record intensities or durations. The typical nonrecording rain gage consists of a collector above a funnel that concentrates precipitation in a container where rainfall depth is measured manually. The size of the mouth of the collector is generally 4 to 8 in. (10 to 20 cm), except in areas of heavy snow where a 12-in. (30-cm) gage should be used. The three principal automatic recording devises are: tipping bucket, weighing, and floating type. Only the weighing type is satisfactory for areas with snowfall. Wind shields are essential components of rain gages. Rainfall intensity and duration can be determined from float or weighing recorders by installing timing devices. Essentials of rain gage installation and operation are reviewed in NOAA (1989).

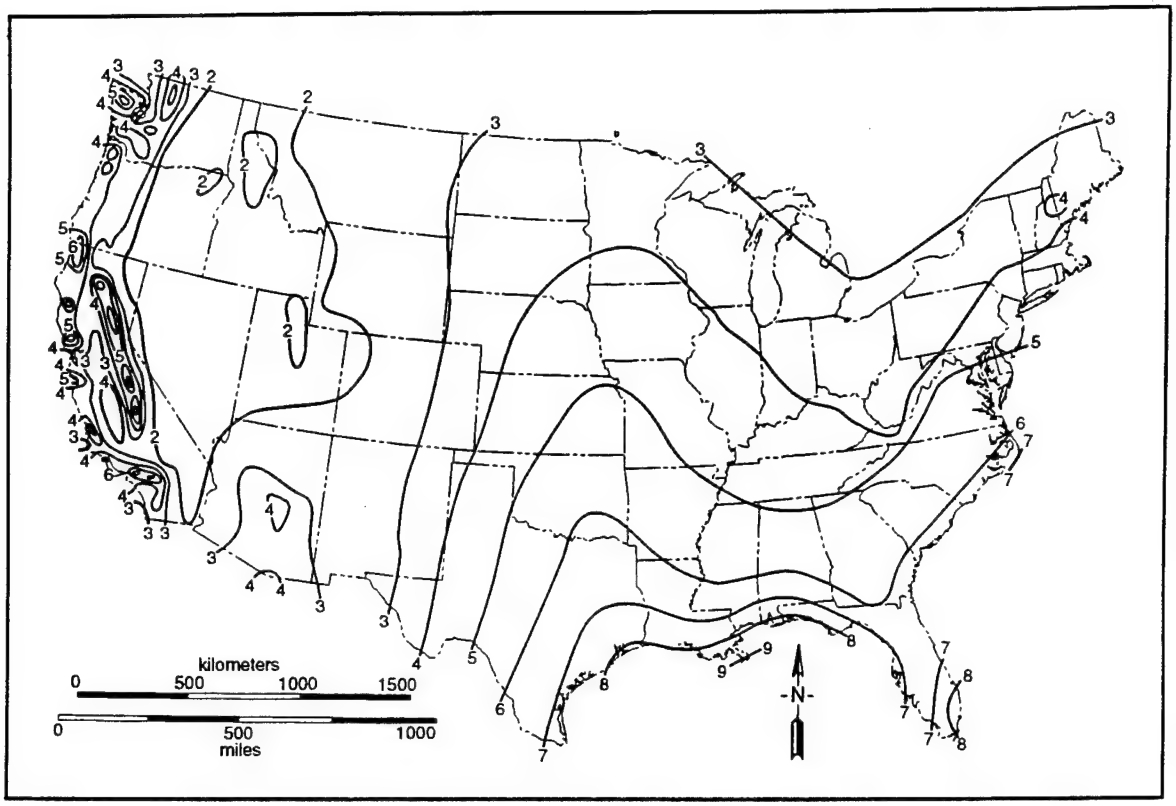


Figure 10. Distribution of rainfall depths, in inches, associated with a 6-hr rainfall event with a probability of recurring once in a 50-year period. (After Hershfield (1961))

Although it may seem straightforward to measure, rainfall estimates across a landscape are rarely precise because rainfall is seldom uniform over a watershed, and a rain gage represents a minute proportion of the area being monitored. Furthermore, inaccuracies are associated with the rain gages themselves and are primarily related to the effects of wind and splash. Caution should also be used with unverified, real-time data because rain gages may become clogged or tipping buckets disturbed by leaves, animals etc. With unverified real-time data, comparison with surrounding rain gages is required; although difficult to quantify, orographic influences should be kept in mind when estimating rainfall measurement error.

Accuracy of gage measurements depends on (a) gage network density, (b) size of the watershed, (c) topography of the watershed, and (d) type of storm including its duration. Because rainfall is generally uneven over an area, the accuracy of gaging decreases with increasing area of estimation (Figure 11). In the example shown by a gray line in Figure 11, a 521-km^2 (200-$mile^2$) watershed with an average annual rainfall of 100 cm (40 in.), which is monitored by two gages, records a 12.5-cm (5-in.) rainfall. The error associated with this measurement is ± 15 percent, or ± 1.6 cm (0.65 in.). In cases where rainfall amounts are sums of catches, such as monthly or annual rainfalls, accuracy increases because the uneven areal distribution of individual events tend to cancel each other over time.

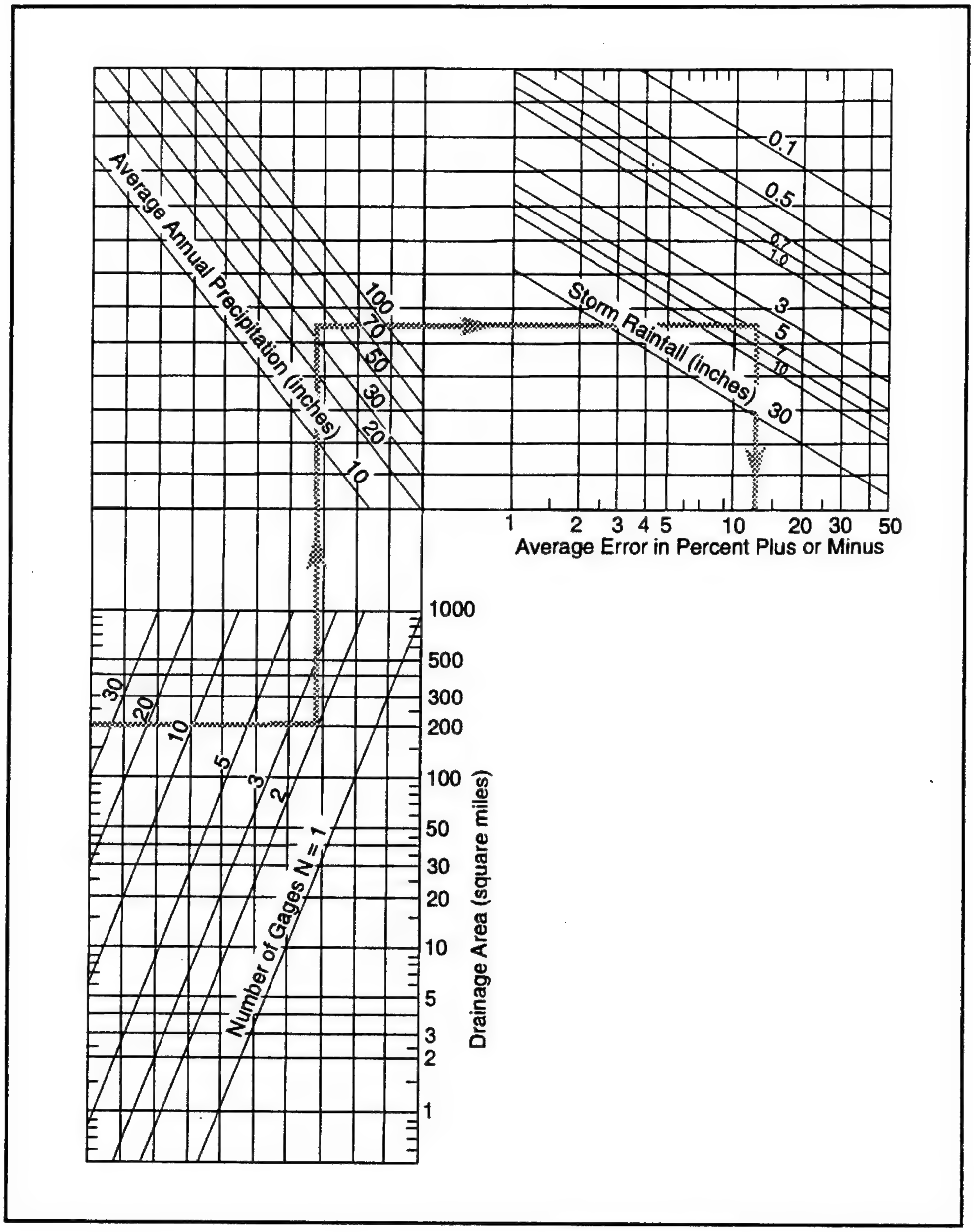


Figure 11. Nomograph for estimating error associated with rain gage measurements

In the case of a network of rain gages in a watershed, the spacing of the gages is rarely uniform enough to take the mean of gage catches as the area average. Two standard methods of estimating rain catches from gage networks are the Isohyetal and Theissen Methods. The Isohyetal Method can be used with networks of any configuration and is particularly useful for examination of rainfall distribution. An isohyet is a line connecting points of equal rainfall depth, and a map is made by drawing the isohyetal lines in a similar manner as contour lines on a topographic map. The Theissen Method divides the watershed into subareas, using the rainfall gages as hubs of polygons (Figure 12). The size of each subarea is determined relative to the overall

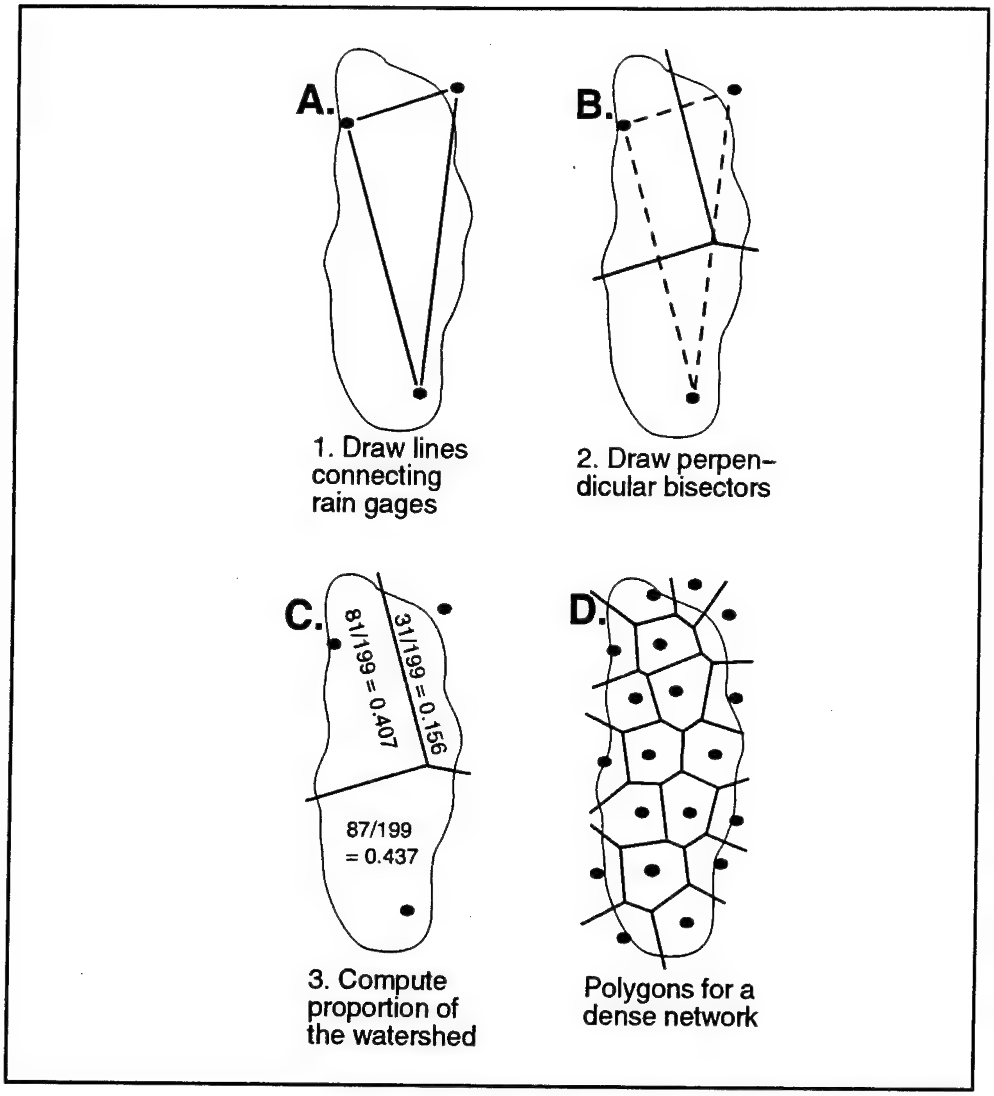
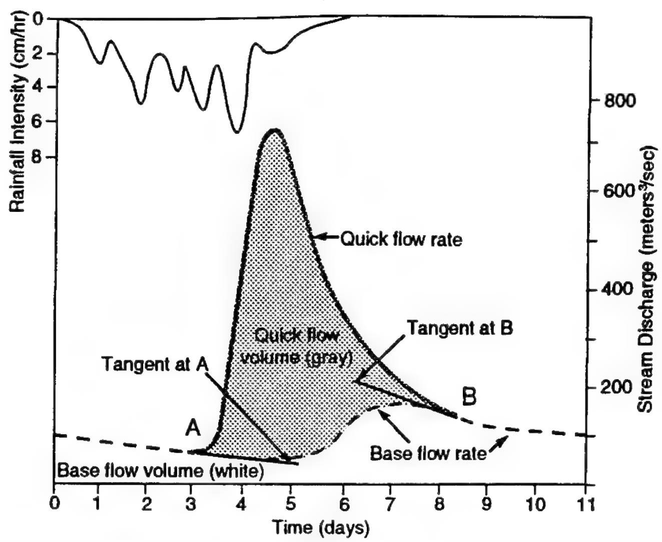


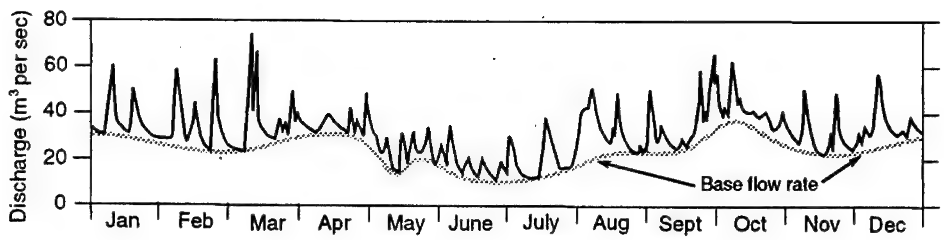
Figure 12. Steps in the determination of Theissen weights. The two lower maps illustrate variations in polygons which is related to the number of rain gages. (After SCS (1972))

size of the watershed, these ratios are multiplied by the subarea rainfall depth, and these subtotals are summed to obtain the watershed average rainfall depth. Regardless of the size and configuration of the rain gage network, there are errors associated with unevenness in the areal distribution of rainfall (Figure 11). Because unevenness of rainfall over an area varies with type of rainfall (thermal convection, frontal convergence, etc.) and topography, Figure 11 does not necessarily provide precise estimates of rain gage errors. It does, however, serve as a reminder that errors are inherent in rain gage estimates of watershed rain catch.

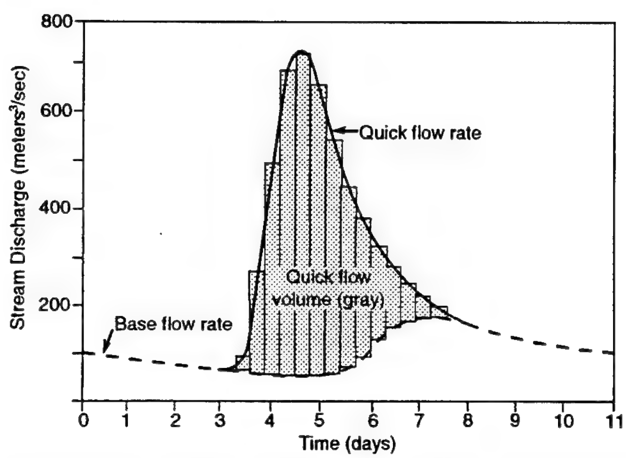
A useful method of recording and analyzing rainfall events is the hyetograph which measures rainfall intensity versus time (Figure 13). As discussed in this chapter in the section entitled Surface water, a hyetograph in



a. Combination hyetograph and hydrograph. Hydrographs distinquish baseflow from quick flow



b. Annual hydrograph showing variation in baseflow



c. Storm hydrograph used to calculate volume of quickflow associated with a rainfall event

Figure 13. Various forms and uses of hydrographs

conjunction with a stream hydrograph can be used to analyze a landscape's response to a rainfall event.

Watershed rainfall depths should be recorded at least on a monthly basis. Rainfall intensity and duration, along with its geomorphic effects, should be recorded for major (recurrence interval of one year or longer) storm events.

Atmospheric water vapor. Even though water vapor in air accounts for only a small fraction (10^{-5}) of the Earth's water at a given time, it is the principal mechanism by which moisture is transferred from the oceans to continents. Atmospheric water constitutes a small fraction of the Earth's water budget at any point in time, but evaporation effectively replenishes the total atmospheric water ~40 times per year so that water which passes through the atmospheric phase per annum is roughly equal to the volume of water that resides in lakes and streams at a given time (Hayden 1988).

Humidity is the measure of the concentration of water vapor in the atmosphere and is commonly expressed in terms of vapor pressure, which is the portion of atmospheric pressure exerted by water vapor. At a given temperature, there is a maximum amount of water vapor that can be held by air; the partial pressure exerted by water vapor in saturated air is known as saturation vapor pressure. As air temperature rises, more water vapor can be held. It follows then that if cooling occurs in unsaturated air, a temperature will be reached at which air becomes saturated, which is termed **dew point**.

Humidity is most commonly reported as **relative humidity** which is the ratio of the actual amount of water in air and the amount that would be present if the air were saturated. Evaporation rates are related to humidity: at a fixed temperature, evapotranspiration rates increase with decreasing relative humidity. Hence atmospheric moisture has an important role in water budgets by exerting an influence on evaporation rates (also see discussion of winds). Fog consists of visible aggregates of minute water droplets suspended in the atmosphere near the Earth's surface. Fogs originate where temperature and dew point of the air become nearly identical (within 2°C), provided that sufficient condensation nuclei are present. Fog drip can be an important source of moisture in areas where fogs occur frequently.

The simplest and most convenient device for measuring humidity is a psychrometer which is composed of a wet- and dry-bulb thermometer. A wet-bulb thermometer is a mercury thermometer with an attached water saturated wick. The psychrometer employs the principles that air is cooled in proportion to the rate of evaporation, and that evaporation from the wick is proportional to the relative humidity. Using tables and nomographs (e.g. Marvin 1941), the difference in wet- and dry-bulb temperature readings can be used to determine vapor content in air. Humidity can also be measured by various types of hygrometers. A dew point/frost point hygrometer is commonly used to measure the temperature at which dew or frost condenses from the air on a cooled surface, usually a mirror. This temperature can be converted into vapor pressure from vapor pressure formulae or tables. Most instruments for

measuring fog density employ one of two techniques: visibility scattering or extinction of light (USGS 1977).

Wind. Winds are the primary transport agent of water vapor from the oceans to continents. They are also the principal generator of ocean wave and current regimes. Winds are the byproduct of uneven heating and cooling of the Earth's surface. In areas which are relatively cool, air tends to descend resulting in excess air volumes and high pressure areas near the Earth's surface. Whereas in areas with relatively warm air, air tends to rise resulting in lack of air mass and low pressure areas near the Earth's surface. Hence air moves in the form of winds from high to low pressure centers, and the magnitude of pressure gradients between high and low pressure centers determine wind velocity.

At the landscape level, winds serve to transport moisture into and out of the system. Winds serve to create lake seiches and local water circulation patterns. Eolian transport of sediment may be a significant part of the material transport regime in some areas. At the landscape level, parameters such as topography, vegetation height and density, and fetch significantly influence the effectiveness of winds. Within a wetland, wind controls water circulation patterns, temperature, and rates of ET.

Whereas most meteorologic phenomena are measured as scaler quantities, wind is a vector, having both intensity and direction. Wind velocities are measured by anemometers (NOAA 1989). The rotating propeller or cup anemometer relates rotational speed to wind speed. The pressure tube or Dine's anemometer is located on the wind end of a weather vane and measures pressure exerted by the wind and converts this measure to velocity. Wind directions, velocities, and frequency of occurrence are commonly summarized in diagrams known as wind roses (Figure 14).

Pressure. Uneven heating of the Earth's atmosphere results in areas of relatively warm and cool air masses. Warm air masses tend to rise and cool air masses tend to fall; rotation of the Earth causes these air masses to behave in a cyclonic fashion (Coriolis effect) such that warm air masses tend to be low-pressure centers (cyclones) and cool air masses tend to be high-pressure centers (anticyclones).

Pressure readings from a region, at a specific time, are routinely plotted on maps and points of equal pressure are joined by isobars. Analysis of the arrangement of pressure centers and their movement over time are an essential tool for predicting weather, because regional patterns of high and low pressure typically produce particular weather conditions. Study of these recurring patterns of regional high- and low-pressure systems and resultant local weather conditions over time are known as **synoptic climatology** and are discussed in more detail in the section entitled Synoptic climatology.

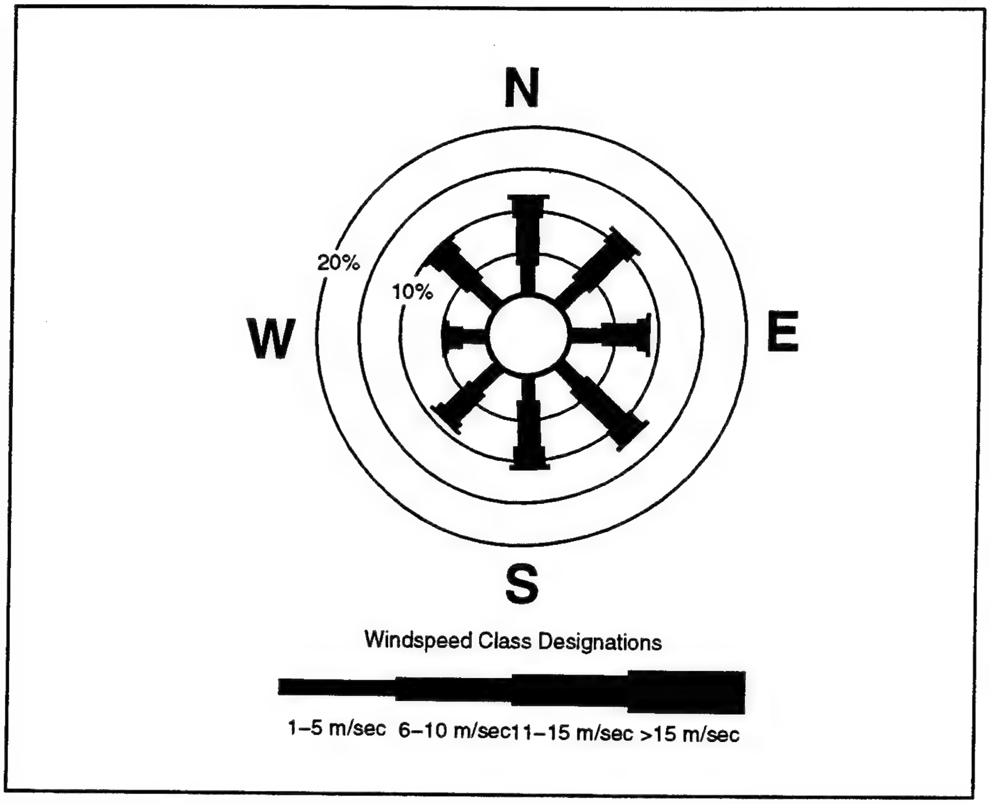


Figure 14. Wind rose summarizes air movement (velocity and direction) in an area over time

Atmospheric pressure is commonly measured using a mercurial barometer in which the total weight of the column of the air mass above the barometer exerts a pressure which is balanced by the weight of the column of mercury. The Fortin barometer is used by the NWS and is recommended for general use (NOAA 1989). Because pressure is monitored at differing elevations, readings must be standardized to a specific altitude, usually sea level.

Evapotranspiration. Conversion of water from liquid to gas and its diffusion into the atmosphere is termed **evaporation**. As an essential part of the hydrologic cycle, evaporation redistributes heat energy between land, water, plants, and the atmosphere (Wiesner 1970). A related process, sublimation, is the conversion of solid ice into vapor without passing through the liquid phase. **Transpiration** is the physiological process by which plants release water into air. Transpiration is essential in transporting water and nutrients from plant roots to leaves. **Evapotranspiration** is the conversion of water to atmospheric vapor by both evaporation and transpiration. The rate of ET is dependent on atmospheric moisture (i.e. vapor pressure gradient at the water-air interface), temperature, wind velocity, and intensity of solar radiation. **Potential ET** is the quantity of soil water capable of being converted to water vapor, in a given climate, by a continuous stretch of vegetation cover situated on soil that is continuously saturated. **Actual ET** is less than potential ET if the ground is not saturated. ET is a principal mechanism of water outflow

from many wetlands and commonly is a principal factor in controlling water chemistry.

The relative importance of evaporation and transpiration in transforming water into vapor is controversial. For example, some researchers contend that plants slow ET by decreasing wind velocities and increasing shade. Whereas others argue that plants act as pumps and accelerate water loss by the process of transpiration. Transpiration, however, is seasonal, and accelerated water loss by transpiration during growing season is generally offset by decreased evaporation resulting from decreased wind velocities and shading throughout the year.

Accurate measurement of ET in wetlands is very difficult because moisture conditions, plant densities, and wind conditions within these systems are highly variable. There are a variety of methods for estimating ET (Wiesner 1970; Mather 1978; Winter 1981). Two basic procedures are described below. There are however many more methods available. More detailed discussions on calculating ET include Wiesner (1970), Winter (1981), and Shuttleworth (1992).

The general water budget method assumes that all hydrologic components of inflow (runoff, precipitation, streamflow, groundwater discharge), changes in wetland storage, and outflow (stream flow, groundwater recharge) are accurately known so that ET can be calculated as the residual of the water balance equation. This is probably the most commonly used method for measuring ET in wetlands. However, measurements of the inflow and outflow components are rarely accurate enough to derive a reliable estimate of ET and therefore serves only as a gross approximation.

It has been widely observed that water levels in vegetated wetlands fluctuate daily in such a way that during the day water levels are consistently lower than at night. These fluctuations have been attributed to enhanced ET resulting in drawdown during the daytime and subsequent replacement by groundwater flow at night (White 1932). A variation of the water budget method uses these diurnal fluctuations in wetland water levels to estimate ET (Heimburg 1984; Dolan et al. 1984; Farrington et al. 1990). The diurnal water table fluctuation technique requires that rainfall and water levels be continuously monitored over a period of time. Shallow observation wells may be necessary if water levels fall below ground level. Graphs of water level versus time are plotted (Figure 15). The steep drop in water level during the daytime represents outflow related to ET (Figure 15). The rise or fall of water levels during the night represents net flow of water into or out of the wetland by hydraulic forces alone. The rate of change of water level during the night is extrapolated up to noon the following day and back to noon the previous day. These extrapolated water levels correspond to the position of the water table if no ET had occurred. The difference in elevation extrapolated from the previous night to the following night represents ET for that day.

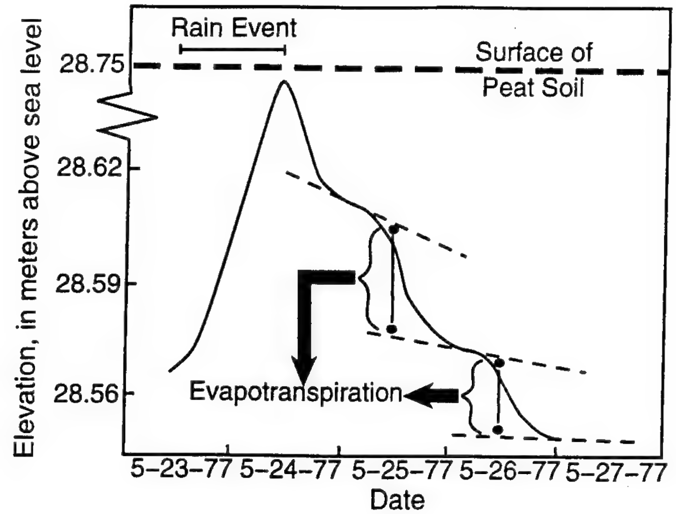


Figure 15. Example of diurnal water-level fluctuations related to ET with the superimposed effect of a rainfall event. (After Dolan et al. (1984))

Some precautions are necessary when utilizing the diurnal water fluctuation procedure. This method applies only if the wetland is relatively isolated from other water bodies and its water table is consistently higher or lower than the surrounding water table so that net flow into or out of the wetland is constant. This method does not work if the surrounding water table is nearly level with the wetland because inflow or outflow will vary on a diurnal basis. If part or all of the water level is below ground level, observed water level changes do not directly measure the actual quantity of water lost through ET. That is, water level changes must be corrected for soil volume which is done by calculating the soils specific yield. **Specific yield** is the amount of water that would drain from a soil if the water table were to be dropped a unit distance. Specific yield is discussed in more detail in the section entitled Soils. Heimburg (1984), Dolan et al. (1984), and Farrington et al. (1990) provide more details on the diurnal water level fluctuation method for calculating ET.

Evaporation pans are the most common instrument used for measuring evaporation. Evaporation data in the United States is generally obtained through class A pan evaporation measurements. A **class A evaporation pan** consists of a Monel Metal (mostly nickel-copper) pan, 120.6 cm (47.5 in.) in diameter, 25.4 cm (10 in.) deep, and is generally supported 5 to 10 cm (2-4 in.) above ground. Water is maintained 5 cm (2 in.) below top. Free water surface (FWS) estimates from pan measurements must be adjusted for heavy winds, heavy rains, and below-freezing temperatures (Farnsworth, Thompson, and Peck 1982). Research has shown that class A pan evaporation measurements are greater than natural lake evaporation so that a coefficient is applied to relate pan to FWS evaporation. The primary reason for variations between pan and FWS evaporation is energy exchange (ga in.) through the

sides and bottom of the class A pan. Farnsworth, Thompson, and Peck (1982) provide a pan coefficient distribution map for the United States.

Other principal methods for calculating ET include empirical (Blaney and Criddle 1950; Thornthwaite and Mather 1957; Mather 1978), aerodynamic (Meyboom 1967; Winter 1981), and energy budget (Winter 1981, and combination (Penman 1948; Wiesner (1970). Figure 16 is a nomograph for estimating evaporation based on the combination method. The example shown by a gray line in Figure 16 records a landscape with solar radiation of 550 langleys, dew point temperature of 1.7°C (35°F), and a wind speed of 161 km (100 miles) per day which produces an evaporation estimate of 0.5 cm (0.2 in.) per pay. Although simplified, Figure 16 is a brief reminder of meteorologic elements that most strongly control ET. It is of note, however, that the nomograph in Figure 16 does not account for water temperature which can have a strong influence on ET rates. Figure 17 summarizes the distribution of precipitation minus evaporation across the conterminous United States. This map serves as a general guide to the overall contribution of the atmospheric component in the water budget.

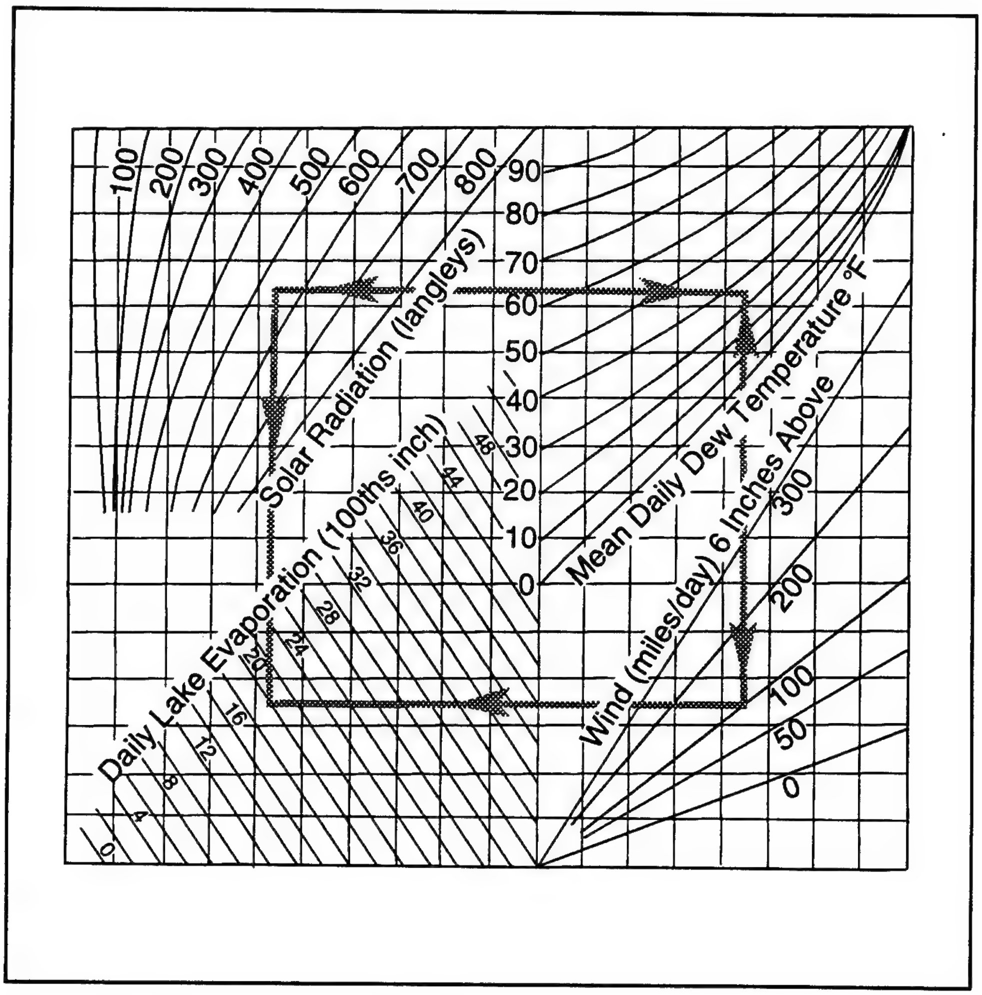


Figure 16. Nomograph for estimating evaporation

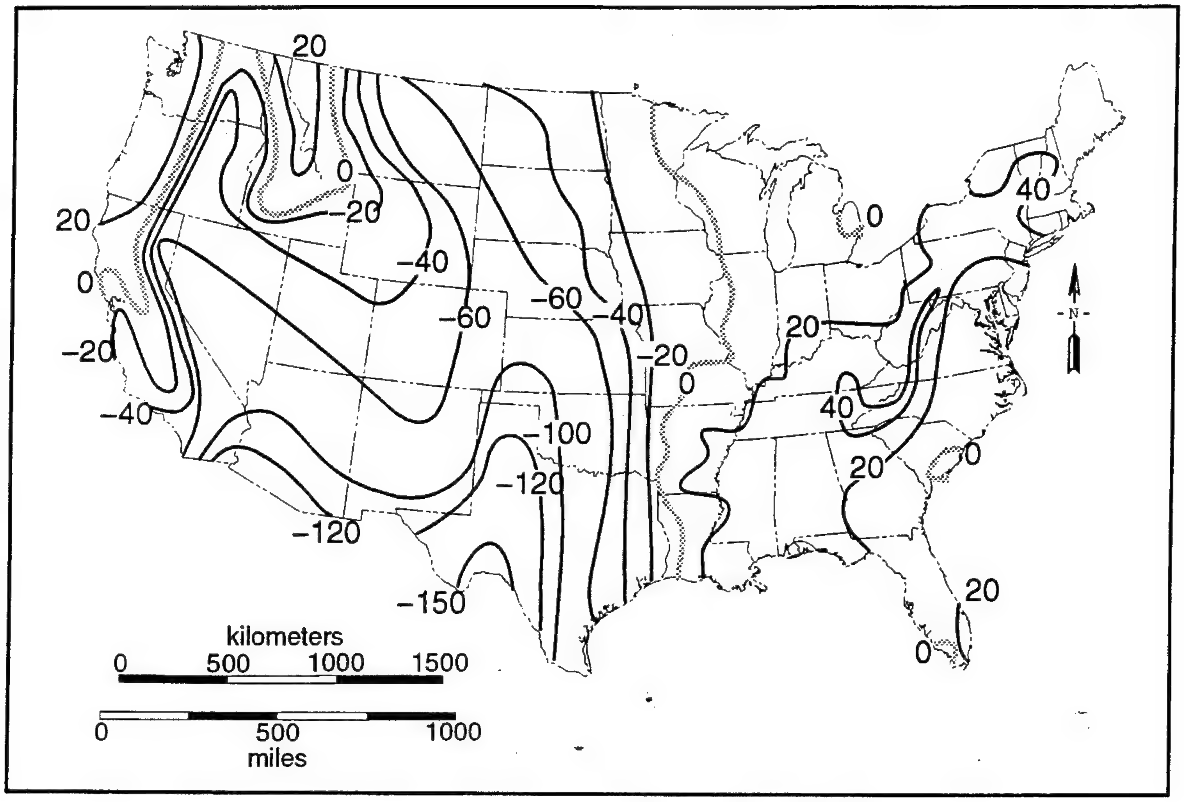


Figure 17. Distribution of the difference between precipitation and open-water evaporation (in centimeters). (Modified from Woo and Winter (1993))

Synoptic climatology

In temperate climates, which control much of the conterminous United States, large-scale pressure cell patterns tend to recur and therefore can be classified into a limited number of types (Figure 18). These synoptic patterns produce predictable local weather conditions. For example, summer droughts in the southeastern United States are associated with frequent recurrence of high-pressure (anticyclonic) conditions off the eastern seaboard (Muller 1977; Yarnal 1993). Description and explanation of local weather in terms of large-scale pressure cell patterns is known as **synoptic climatology**. By relating local weather to a defined set of synoptic weather patterns and monitoring these configurations over time, synoptic climatology provides a baseline to evaluate local and regional climatic variations and the response of landscape forms and processes to these climatic variations. In terms of wetland systems management, synoptic climatology provides a means to evaluate current weather conditions in relation to long-term averages, relate long-term weather patterns to the capacity of a wetland to provide particular functions, and evaluate the degree to which changes in wetland form and function are related to changes in long-term weather patterns.

To illustrate the use of synoptic indices as a baseline for environmental analysis, Muller's (1977) characterization of weather of New Orleans, LA, in

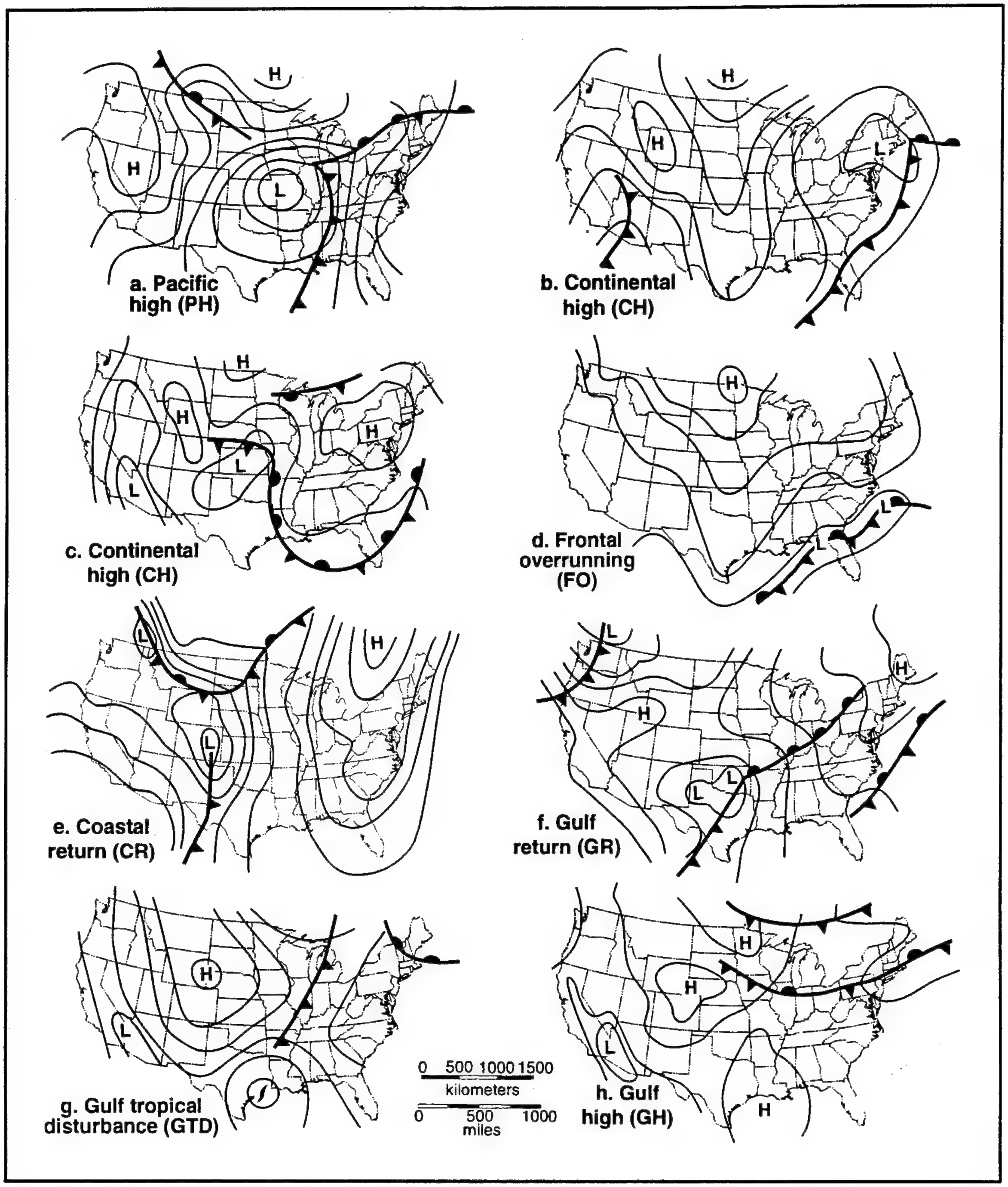


Figure 18. Synoptic weather types as compiled at New Orleans 1971-1975

terms of synoptic weather types is discussed. Muller (1977) and Yarnal (1993) provide more thorough descriptions of synoptic climatology.

Daily atmospheric circulation patterns at 0600 and 1500 Central Standard Time from the weather station at Moisant Airport in New Orleans were compiled and Muller (1977) found that circulation patterns could be classified into eight synoptic weather types (Figure 18). An inventory of frequencies, by month, of the occurrence of the eight synoptic weather types demonstrated

that each type tended to occur on a seasonal basis and was correlated with shifts in the circumpolar wave pattern. Then, local weather conditions were related to the eight synoptic types by (a) compiling average daily readings of temperature, precipitation, relative humidity, wind speed and direction, and cloud cover; (b) assigning these average daily weather readings to the synoptic weather pattern of the day; and (c) averaging, by month, the temperature, precipitation, relative humidity, etc. associated with each synoptic type (Table 15). From the compiled mean monthly information, generalizations about the relationship between local weather and synoptic weather types was deduced. For example, the gulf return (GR) pressure cell pattern (Figure 18) most commonly occurs in spring and early summer, and induces warm, cloudy, humid conditions and a variable possibility of rain in the New Orleans area.

Table 15
Mean Local (New Orleans) Weather Conditions Associated with Synoptic Atmospheric Patterns for January 1971-1974

	Synoptic Weather Types (See Figure 18 for full names)							
	PH	CH	FO	CR	GR	FGR	GTD	GH
0600 Central Standard Time								
Number of occurrences	8	17	37	8	30	18	0	5
Air temperature (°C)	9.6	3.2	8.2	8.9	16.4	19.3	-	9.3
Dew-point temperature (°C)	8.2	-0.6	4.8	7.3	15.6	17.8	-	7.0
Relative humidity	92	78	81	89	93	91	-	65
Wind direction	34	04	01	12	14	17	-	35
Wind speed (ft/sec)	7.2	12.5	17.1	7.5	9.8	13.4	-	6.2
Cloud cover	4	1	9	7	9	9	-	4
1500 Central Standard Time								
Number of occurrences	8	19	33	9	30	20	0	5
Air temperature (C)	19.2	12.3	11.6	16.1	22.7	22.2	-	18.7
Dew-point temperature (C)	8.8	-.01	7.0	9.0	16.8	18.2	-	5.0
Relative humidity	53	45	76	64	70	76	-	48
Wind direction	32	36	01	07	16	19	-	30
Wind speed (ft/sec)	13.4	15.4	17.4	14.4	18.4	15.1	-	13.8
Cloud cover	2	1	10	6	7	10	-	4

After Muller (1977).

To further analyze relationships between regional and local weather conditions, Muller (1977) combined the eight synoptic weather types into three environmental baseline indices: storminess, continental polar, and maritime tropical. Storminess combines frontal overrunning (FO), frontal gulf return (FGR), and gulf tropical disturbance (GTD) types (Figure 18). The continental polar index combines the continental high (CH) and frontal overrunning (FO) types (Figure 18). This index is associated with cool dry weather, is most common in late fall but persists until June, and is related to the southerly

migration of the jet stream during the winter. The maritime tropical index includes gulf return (GR), frontal gulf return (FGR), gulf tropical disturbance (GTD), gulf high (GH), as well as coastal return (CR) during July through September (Figure 18). The warm, humid weather associated with this index is most common in the summer and is dominated by temperature and moisture conditions originating in the Gulf of Mexico.

To study general trends in the frequency of occurrence of environmental baseline indices over time, departures of the three environment baseline indices from their mean occurrence were plotted (Figure 19). For example, the synoptic types associated with the storminess index occurred 65 percent of the time in 1971. The mean percent occurrence of the storminess index for the month of December 1971 to 1975 was 47 percent. Therefore its departure for 1971 was +18 percent, reflecting unusually high rainfall amounts for that year. Two uses of this graph are: evaluating long-term changes in the relative influence of the three indices, and correlation of unusual or changing

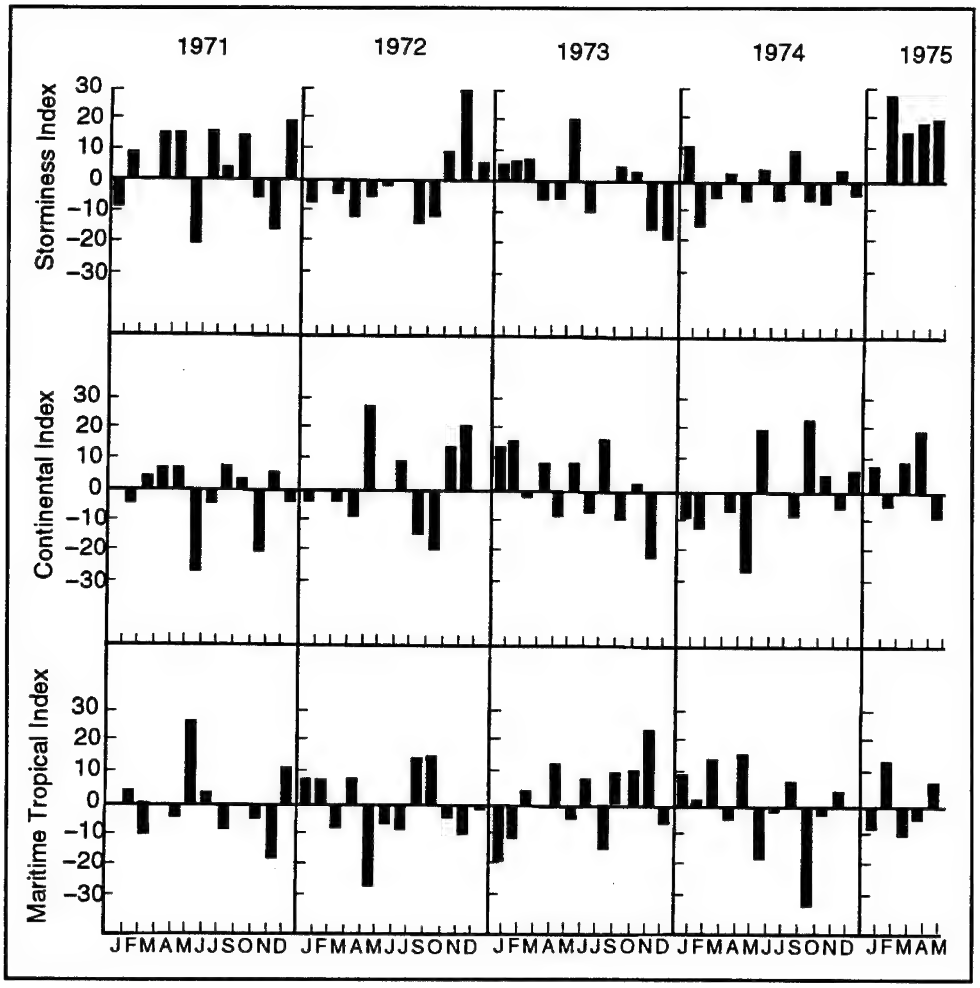


Figure 19. Departures of mean monthly environmental baseline indices from the 4.5-year average frequency of occurrence. Environmental baseline indices are discussed in text. (After Muller (1977))

weather conditions to frequency of occurrence of these indices. Muller (1977) discussed other actual and potential uses of the environment baseline indices.

Departures of temperature and precipitation from long-term means were plotted (Figure 20). Figure 20 reveals that mean monthly temperatures tend to cluster into 6 to 12 month high and low periods. Muller (1977) related these semiannual to annual shifts to changes in the circumpolar vortex. This semiannual to annual fluctuation did not occur in the precipitation; instead, precipitation patterns reflect unusually high precipitation recorded for the 1971 to 1975 period.

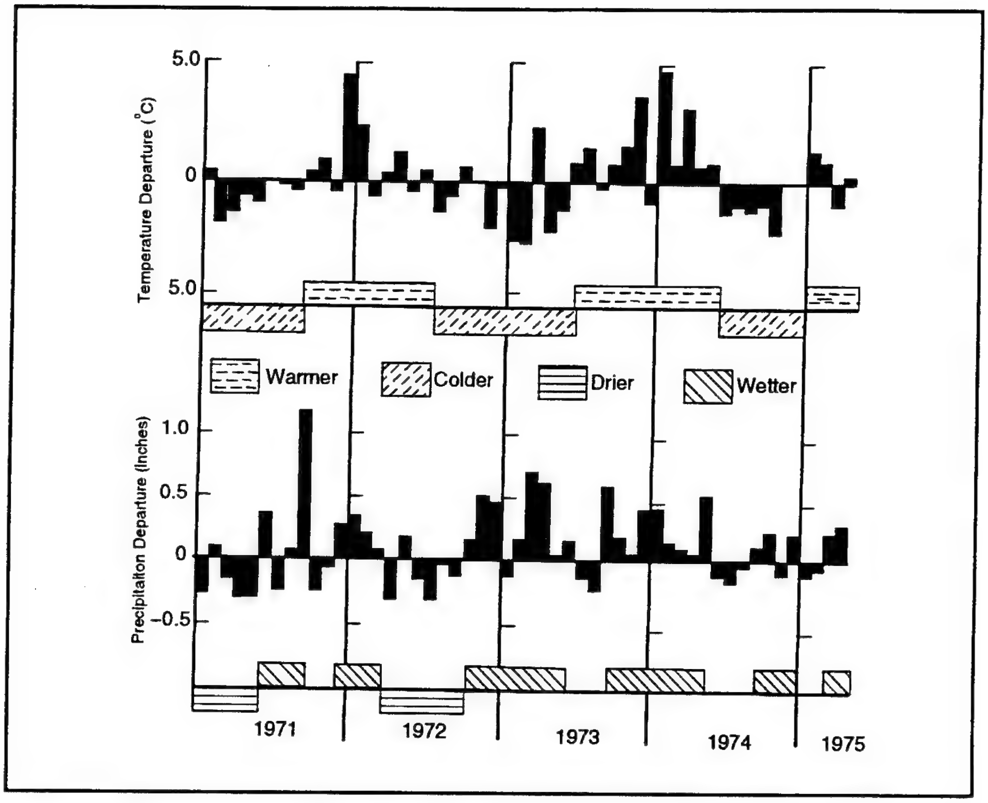


Figure 20. Departure of mean monthly temperature and precipitation from long-term (1931 through 1960) averages. (After Muller (1977))

The eight synoptic weather types of Figure 18 are generally applicable for the conterminous United States, although the West is also influenced by Pacific pressure cells and the East by Atlantic cells. Weather associated with these synoptic types, however, varies locally, and thus environmental baseline indices will be different from region to region. Regional synoptic climatologists, who are commonly associated with university geography departments, can be consulted for more site specific analysis.

Landscape equilibrium states are largely controlled by long-term climatic cycles. These cycles take place over decades, centuries, or even longer (Figure 5). A major challenge in evaluating landscape systems is distinguishing shifts in hydrologic conditions resulting from periodic, high intensity natural

events, long-term shifts in climatic conditions, and human activity. Evidence, such as tree-ring, ice core, and stratigraphic data suggest that climatic changes in North America were greater in the past 10,000 years than any measured in the past 100 years. However, these millennia-scale data are not at a time resolution sufficient to allow meaningful analysis of current climatic trends, and recent climatic data have not been collected over a long enough time interval to distinguish long-term climatic trends. Synoptic climatology, however, provides a basis for monitoring climate shifts on a decadal scale.

Geology and Soils

A landscape reflects the balance between force (climate, gravity, hydrology, and, to some degree, biology) and resistance (geology and, to some degree, biology). Resistance has two forms: active and passive. Active resistance is generated by processes deep in the Earth and is manifest by such phenomena as tectonic uplift, volcanism, and subsidence. Passive resistance is associated with the composition, texture, and structure of earth materials. Passive resistance is related not only to the physical strength of the material but also to its ability to resist alteration (weathering). Force and resistance interact to produce the processes of weathering, erosion, transport, and sedimentation. These four processes are the fundamental mechanisms controlling landscape evolution. Their geomorphic effectiveness and capacity to do work are controlled by the balance of intensity of forces acting on the system and the capacity of earth material to resist change.

Geology also influences landscape evolution by controlling the flow of water and materials through the landscape. Geologic parameters which influence hydrology include lithology (rock and sediment composition), soil type, porosity, permeability, structure (arrangement of rock and sediment in 3-D space), and fractures.

Soils are the dynamic interface between climate, geology, hydrology, and biology. Soil composition influences floral abundance and diversity, the proportion of runoff to infiltration, moisture storage, and the rate of shallow groundwater flow. In addition, geotechnical properties of rock, sediment, and soils influence erosion rates and slope stability.

Geologic phenomena occur over a wide range of time scales (Figure 4). Based primarily on fossils, the relative position of undisturbed sedimentary layers (younger overlie older strata), cross-cutting relationships (younger cross-cut older rocks), nineteenth century geologists devised the geologic time scale in which ages were relative (Figure 21). It was only in the latter half of the twentieth century, using of radiometric age dating techniques, that actual years were assigned to the geologic time scale. Note that in the following discussion the preQuaternary (1.6 million years and older) is differentiated from the Quaternary (1.6 million years and younger) Periods, and the Quaternary is subdivided into the Pleistocene and Holocene Epochs. Termination of

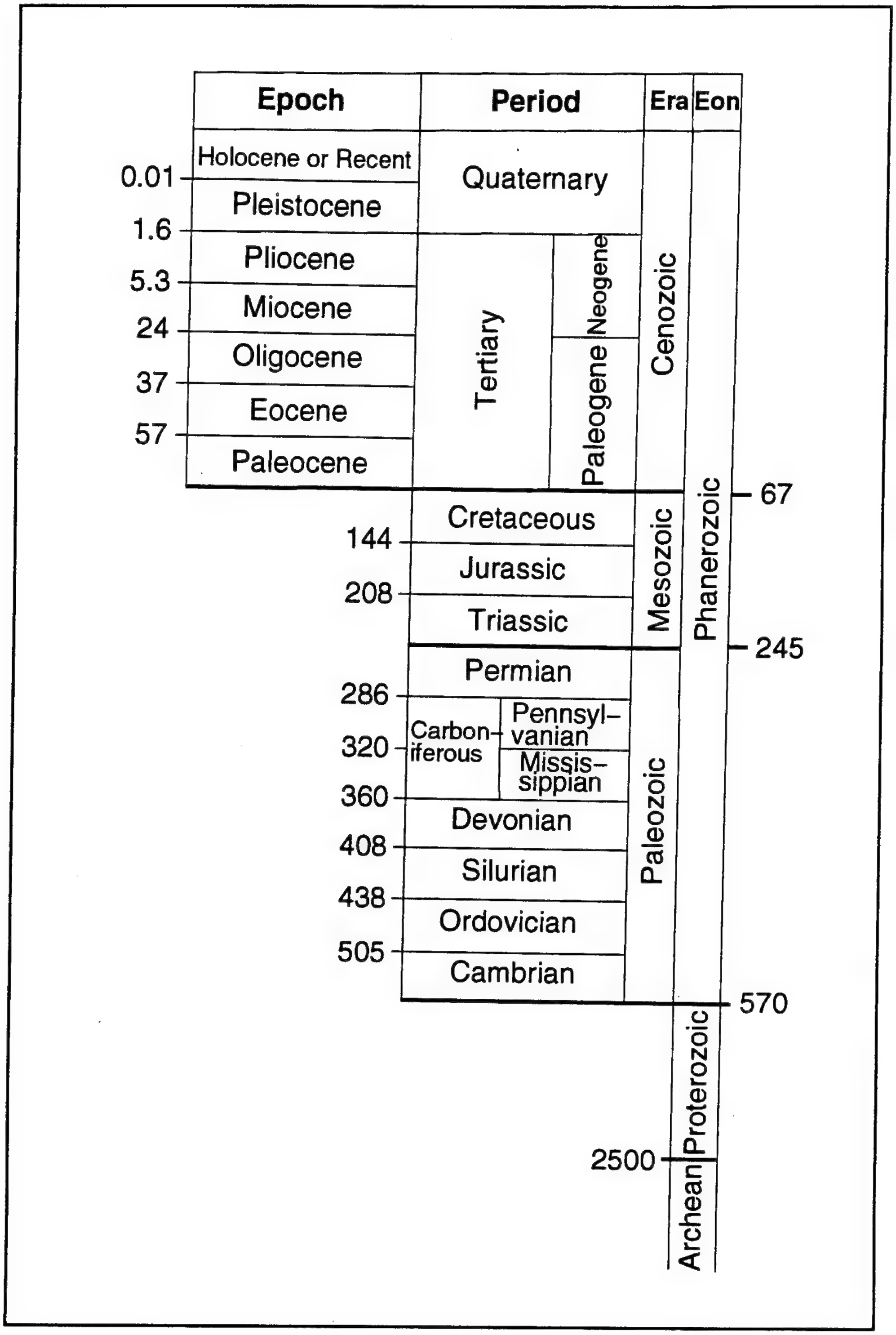


Figure 21. The geologic time scale. Numbers at sides of columns are approximate ages in millions of years

the last glacial epoch, which was critical in the development of many extant wetlands, occurred about 10,000 years ago, at the beginning of the Holocene Epoch.

The Geology and Soils section of this report begins with a review of sources for geologic data. Then a brief description of earth materials: pre-Quaternary bedrock, Quaternary sediments, and soils is given. Next, the four major landscape forming processes, weathering, erosion, transport and deposition, are discussed. Methods for evaluating the flow of material through a landscape is presented. Then geomorphic principles and methods are briefly discussed.

Geologic data sources

All states have geological surveys which are invaluable sources of information on local and regional geology. The regional USGS Earth Science Information Centers are also excellent sources of data (Table 10). State geologic maps are available for most of the United States, however, these are too broad scale to be of much use in evaluating landscapes, except to describe the regional setting. More detailed geologic maps of counties and 15- and 7.5-min quadrangles may be available from the USGS, state geological surveys (Tables 8 and 10), universities, and from private engineering, construction material, mining, and fossil fuel companies.

Soil survey maps are available from county offices of the NRCS. Modern soil surveys provide information on soil properties such as: soil slope, soil drainage class, particle size distribution, soil structure, bulk density, permeability (hydraulic conductivity), water capacity, acidity, alkalinity, depth to bedrock, depth to water table, soil-erosion factors K and T, hydrologic soil groups, and infiltration rates (USGS 1977). Soil surveys are becoming available in digital form for many areas of the United States.

Earth materials

A basic classification of rocks and sediments, and some of their fundamental characteristics are presented in Figure 22. **Rocks** are cohesive aggregates of grains of one or more mineral types. **Minerals** are naturally occurring, solid, inorganic elements or compounds, with a definite composition or range of compositions, usually possessing a regular internal crystalline structure (e.g., quartz, calcite).

There are three principal rock types: igneous, metamorphic, and sedimentary. **Igneous** and **metamorphic** rocks tend to be highly crystallized (have very low porosities) and indurated. Igneous and metamorphic rocks form at temperatures and pressures far greater than Earth surface conditions which cause their mineral constituents to be unstable (vulnerable to weathering) at the Earth's surface, particularly in the presence of water. In general, the higher the temperature and pressure conditions under which rocks and

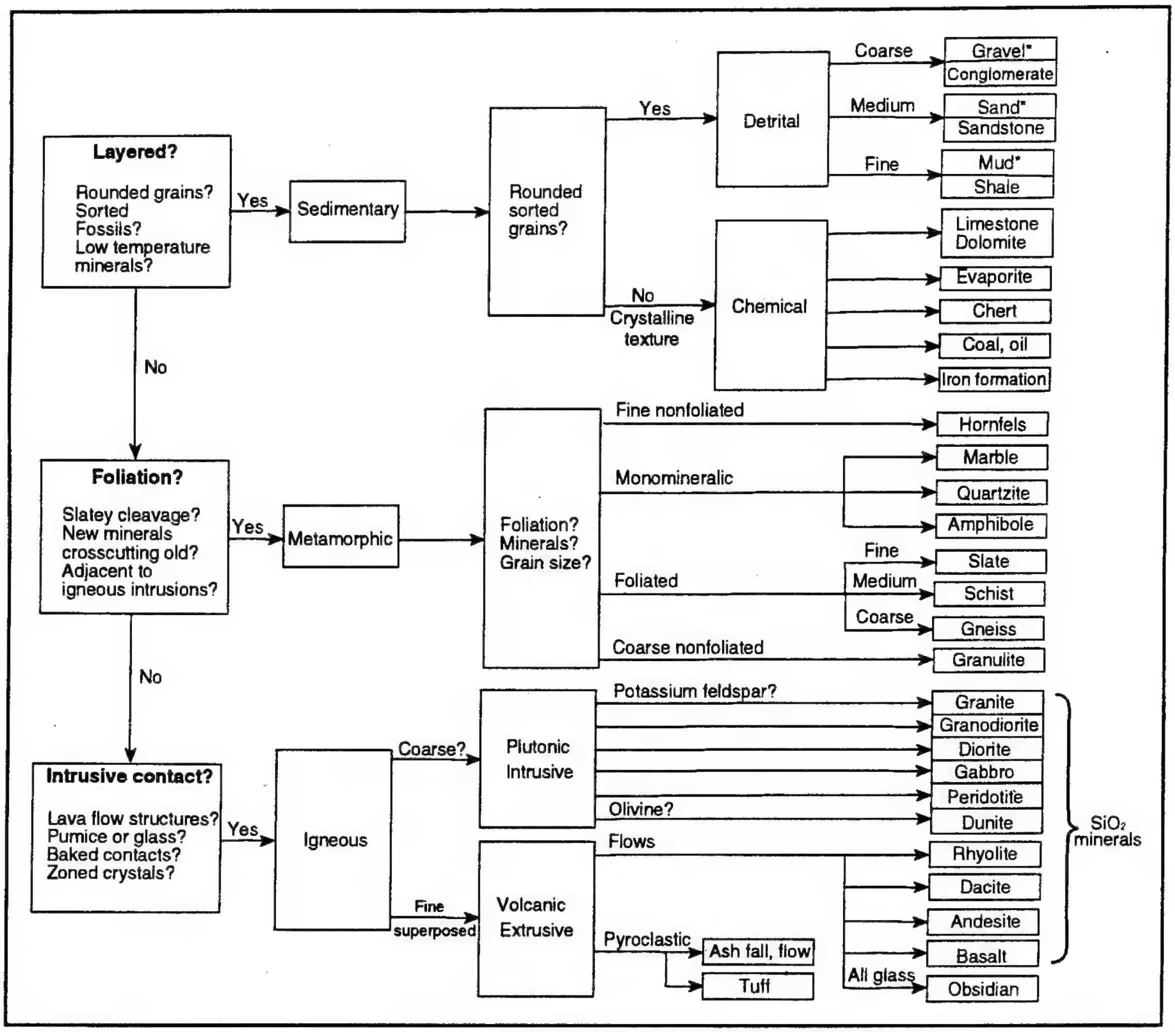


Figure 22. Rock identification flow chart. Actually gravel, sand, and mud (indicated by asterisk) are sediments; whereas conglomerate, sandstone, and shale are their rock equivalents. (After Press and Sevier (1986))

minerals form, the more easily they react with water to dissolve and/or form minerals (mostly clays) that are stable under earth surface conditions.

Sediments are either **lithified** or **unlithified**, that is their minerals components are either bound together by mineral cement or not. Sediment consolidation generally involves burial and solution-reprecipitation of certain mineral components by groundwater. Consolidation markedly decreases permeability of sediments and increases resistance to erosion. Unconsolidated sediments are known simply as **sediments**, or perhaps as soils to engineers (see discussion of the term soil in the section entitled Soils). Consolidated sediments are known as **sedimentary rocks**.

Prequaternary (or bedrock) geology. Bedrock is a general term used for rock that underlies soil or other unconsolidated, surficial material. Bedrock composition and geometry are major controls on watershed configuration, relief, surficial drainage pattern, and soil composition.

Bedrock porosity and permeability are major controls in water flow through a landscape. Rock porosity and permeability are determined by (a) rock type, (b) jointing and fracturing, and (c) degree of alteration by surface water and groundwater. Sediments vary in porosity from >30 percent (unconsolidated sand) to ~0 (highly consolidated sandstones, limestones, and shales). Igneous and metamorphic rocks at depth have essentially no porosity. However, as deeply buried rocks are exhumed and the weight of the overlying rock is removed, rocks expand and fracture, so that essentially all rocks near the Earth's surface are at least microfractured and therefore are at least slightly porous and permeable (Figure 23).

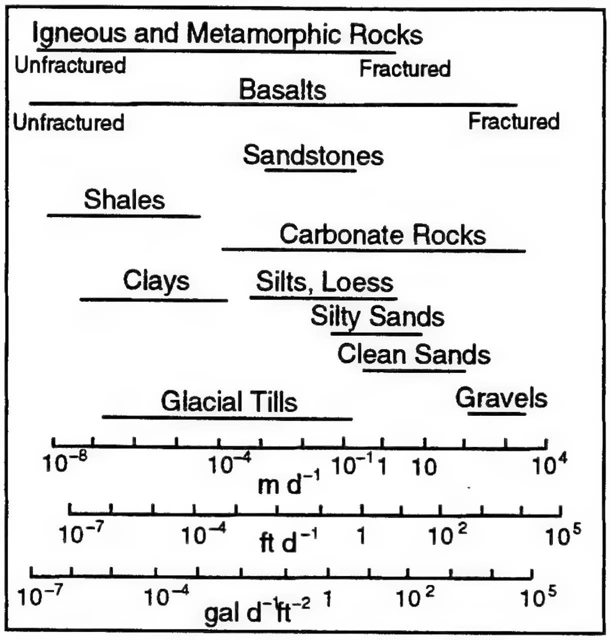


Figure 23. General relationship between rock and sediment type and hydraulic conductivity. (After Heath (1983))

Most areas of the United States have experienced regional tectonic stresses which have produced widespread fractures, **joints** (a fracture in a rock without actual displacement), and lineaments (regional-scale linear features). Because the tectonic forces that produce joints and lineaments are not random, these planar features tend to be oriented in specific directions within a region. Joints and fractures greatly enhance rock permeability and thereby decrease resistance to weathering. In regions with little perceptible structural deformation, both groundwater flow and surficial drainage patterns may be strongly influenced by jointing. Lineament analysis using topographic maps, aerial photographs, and other remote sensing imagery is commonly carried out to evaluate principal jointing and fracturing directions (Siegal and Gillespie 1980). However, information regarding lineaments obtained from remote sensing data should be substantiated with other information sources.

Many regions of the United States have experienced structural deformation, i.e., folding and faulting. **Folds** are bent or warped rock layers, which were originally horizontal, and subsequently deformed. **Faults** are planar or gently curved fractures in the Earth's crust across which there has been relative displacement. Folding of rock layers (strata) enhances fracturing and exposes strata of variable resistance to the Earth's surface so that the overriding controls on topography become the distribution of strata and their relative resistance to erosion (Figure 24). In areas of folded strata, watersheds tend to be elongate such that valleys are parallel to the axes of folds. In such areas, valleys are typically underlain by easily erodible shales, and ridges are underlain by resistant sandstones. Heterogeneities in the subsurface caused by folding result in complex groundwater flow systems. Faulting can also disrupt groundwater flow systems by offsetting aquifers and altering porosity and permeability along the fault plane. Faulting can exert control on the topography and surface hydrology of a watershed by juxtaposing rocks and strata of variable resistance, thereby altering surface drainage systems (Figure 24).

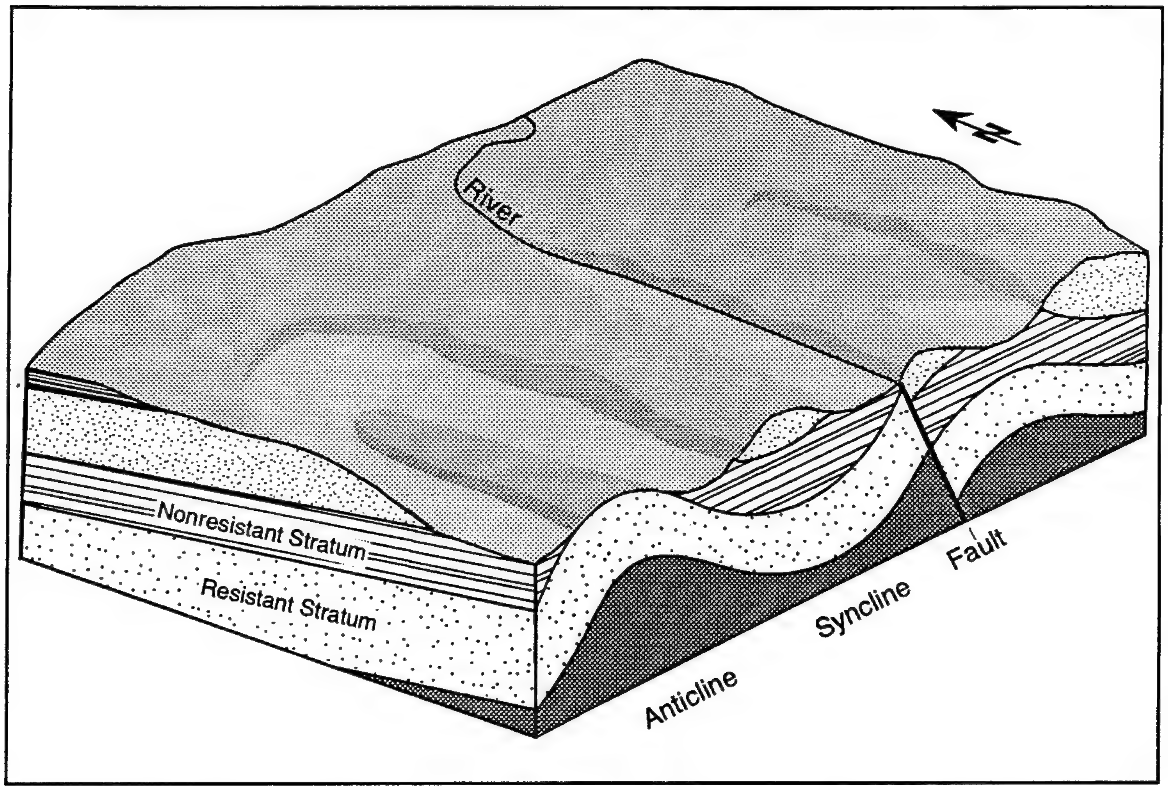


Figure 24. Block diagram showing general relationships between geologic structures and topography. Note that topographic highs may be associated with the cores of either synclines or anticlines. In the diagram, the axes of the synclines and anticlines are inclined (plunging) to the north. Note that the fault disrupts the sinuous surface expression of the plunging folds and alters the course of the river

Quaternary geology. Naturally occurring wetlands of the conterminous United States have formed in three principal environments: glacial, fluvial, and coastal (Kusler 1987); nearly all of these wetlands are underlain by

semiconsolidated to unconsolidated Pleistocene and Holocene sediments. These sediments, whose transport and accumulation are generally related to the termination of the latest glacial epoch and onset of current interglacial conditions, have an overriding influence on the wetland landscape by controlling local relief, groundwater and surface water hydrology, soil formation, and wetland form and extent. Late Quaternary sediments that immediately underlie wetlands are commonly depicted on geologic maps as one unit (Quaternary alluvium); at a landscape level, however, their hydrogeologic properties are complex.

Sediments typically occur in layered or lenticular form. Contrasting layers reflect changes in sediment composition and grain size that record changes in the physical environment which brought about sediment input and deposition. Layered sedimentary units are referred to as **strata**. **Stratigraphy** is the geologic study of the composition, form, arrangement, geographic distribution, correlation, chronologic succession, and history of layered sediments. **Sedimentology** concentrates on sediment composition and bedform, and the processes which generate them.

Stratigraphic analysis not only provides information regarding the origin, history, and paleogeography of sediments, it provides vital information regarding groundwater flow (i.e., geometry and distribution of water-bearing units). Furthermore, coring, sediment analysis, and subsequent construction of cross sections are fundamental sources of information regarding a wetland's development and history. Schoch (1989) provides a more thorough review of stratigraphic concepts and methods.

Soils. Soil development is an ongoing geologic process which involves *in situ* alteration of rocks and sediments. Soils are the dynamic interface of geology and climate. Plants, animals, and microorganisms, whose distribution is at least in part controlled by geology and climate, also influence soil development. Five key factors of soil formation are: parent material, climate, organisms, slope, and time.

It is useful to recognize that the meaning of the term "soil" is not necessarily the same to geologists, engineers, and soil scientists. Engineers and geologists commonly use the term "soil" to refer to the surficial layer of altered rock or sediment. Thus, for engineers and geologists, soil might include all or part of the regolith. **Regolith** is the general term for the entire layer of loose, incoherent, and unconsolidated rock fragments, whether transported or the product of weathering, that nearly everywhere covers the more coherent bedrock. To soil scientists, "soil" refers to well stratified (i.e., coherent) earth material, commonly 3 to 6 ft thick, that supports or is capable of supporting plants and has formed through the interaction of climate, biological activity, and the rock fragments and mineral grains in the upper part of the regolith (USGS 1977). Herein, the term soil refers to that defined by soil scientists, and follows the NRCS textural (Figure 25) and taxonomic (Table 16) classification.

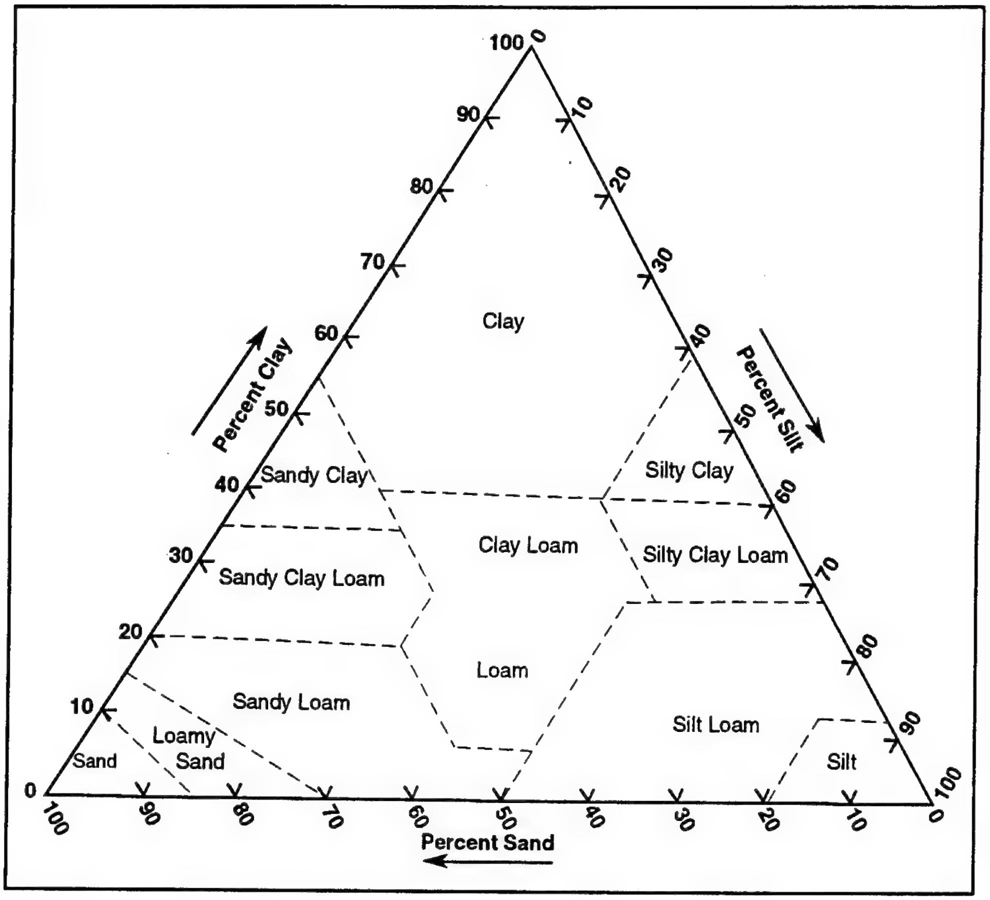


Figure 25. NRCS (formerly SCS) soil texture classification system

Soil types have been related to climate (Figure 26) and to the degree of weathering of the parent material (Figure 27). Caution, however, should be used in relating degree of soil development to its age, because the degree of soil development is a function of resistance of parent material and intensity of processes acting at the Earth's surface, as well as a function of time.

Mature soils are in dynamic equilibrium with the landscape. Soils require hundreds to thousands of years to develop. Volcanism, tectonism, and human activity have caused widespread disequilibrium in soils that has induced accelerated runoff and erosion (Bloom 1991; Hooke 1994). This not only affects the eroded uplands but also increases sediment load to transport and storage components of the landscape.

Wetland soils can be evaluated by soil mass properties, strength, compressibility, and permeability (Leach and Johnson 1994a,b). Mass properties include density, void ratio, and water content. Strength parameters define the ability of soils to support structures and resist erosion. Compressibility properties define the ability of a soil to resist deformation. Permeability properties define a soil's ability to transport water. Leach and Johnson (1994a,b) provide a more detailed discussion of the geotechnical properties of soils. The

Table 16
Summary of Soil Orders Suborders, and Great Groups

A. Names of soil orders, with simplified definitions	
Alfisol	Combined Al and Fe; soil with gray to brown surface horizon, medium to high base supply, and a subsurface horizon of clay accumulation. Formative element: *alf*.
Aridisol	L. aridis, dry; soil with pedogenic horizons, low in organic matter, usually dry. Formative element: *id*.
Entisol	Recent; soil without pedogenic horizons. Formative element: *ent*.
Histosol	Gr. histos, tissue; organic (peat and muck) soil. Formative element: *ist*.
Inceptisol	L. inceptum, beginning; soil with weakly differentiated horizons showing alteration of parent materials. Formative element: *ept*.
Mollisol	L. mollis, soft; soil with a nearly black, organic-rich surface horizon and high base supply. Formative element: *oll*.
Oxisol	From oxidized; soil that is a mixture principally of kaolin, hydrate oxides, and quartz. Formative element: *ox*.
Spodosol	Gr. spodos, wood ash; soil that has an accumulation of amorphous materials in subsurface horizons. Formative element: *od*.
Ultisol	L. ultimos, ultimate; soil with a horizon of clay accumulation and low base supply. Formative element: *ult*.
Vertisol	L. verto, to turn; cracking clay soil. Formative element: *ert*.

B. Principal formative elements to be used in naming suborders.

Names of suborders consist of two syllables. For example, an argalf is an alfisol with a clay horizon.

alb	L. albus, white; soils from which clay and iron oxides have been removed.
aqu	L. aqua, water; soils that are wet for prolonged periods.
arg	Modified from L. argilla, clay; soils with a horizon of clay accumulation.
bor	Gr. boreas, northern; cool.
fluv	L. fluvius, river; soils formed in alluvium.
ochr	Gr. base of ochros, pale; soils with little organic matter.
orth	Gr. true; the common or typical.
psamm	Gr. psammos, sand; sandy soils.
ud	L. udus, humid; of humid climates.
umbr	L. umbra, shade; dark colors reflecting much organic matter.
ust	L. ustus, burnt; of dry climates with summer rains.
xer	Gr. xeros, dry; of dry climates with winter rains.

(Continued)

Table 16 (Concluded)

C. Principal formative elements to be used in naming great groups	
Names of great groups consist of more than two syllables and are formed by adding a prefix to the suborder name. For example, a cryoboralf is an alfisol from cold, northern regions; a tropaquept is an inceptisol that is wet for prolonged periods and is located in a warm humid climate.	
cry	Gr. fryos, icy cold; cold soils.
dystr, dys	Gr. dys, ill; infertile.
eutr, eu	Gr. eu, good; fertile.
frag	L. fragilis, brittle; a brittle pan.
gloss	Gr. glossa, tongue; deep, wide tongues of albic materials into argillic horizon.
hapl	Gr. haplous, simple; the least advanced horizons.
quartz	Ger. quarz, quartz; soils with high quartz content.
torr	L. torridus, hot and dry; soils of very dry climates.
trop	modified from Gr. tropikos, of the solstice; humid and continually warm.
L. = Latin; Gr. = Greek; Ger = German	
Source: Bloom (1991); Twidale (1990); SCS (1992).	

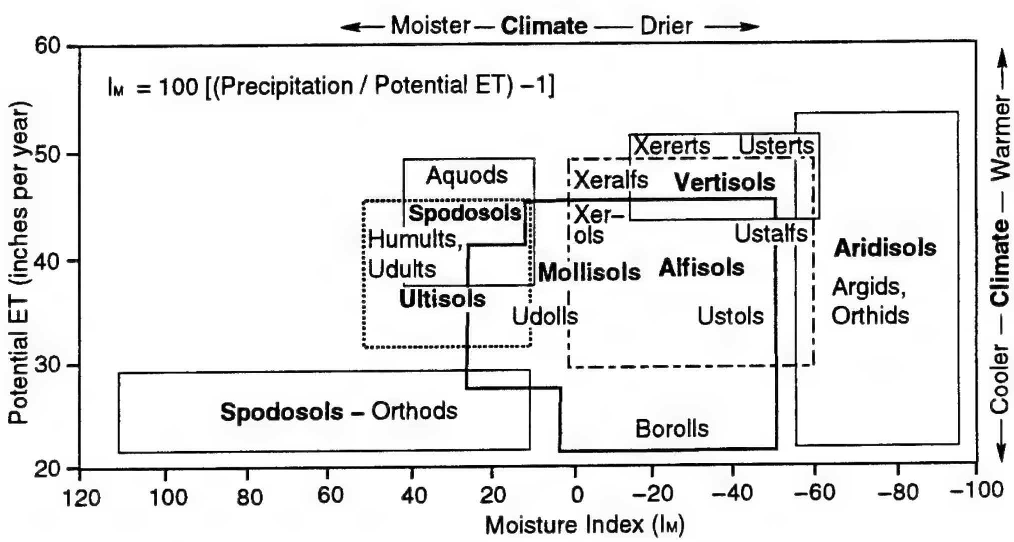


Figure 26. Schematic relationship between potential ET, moisture index, and selected soil classes. (After Mather (1978))

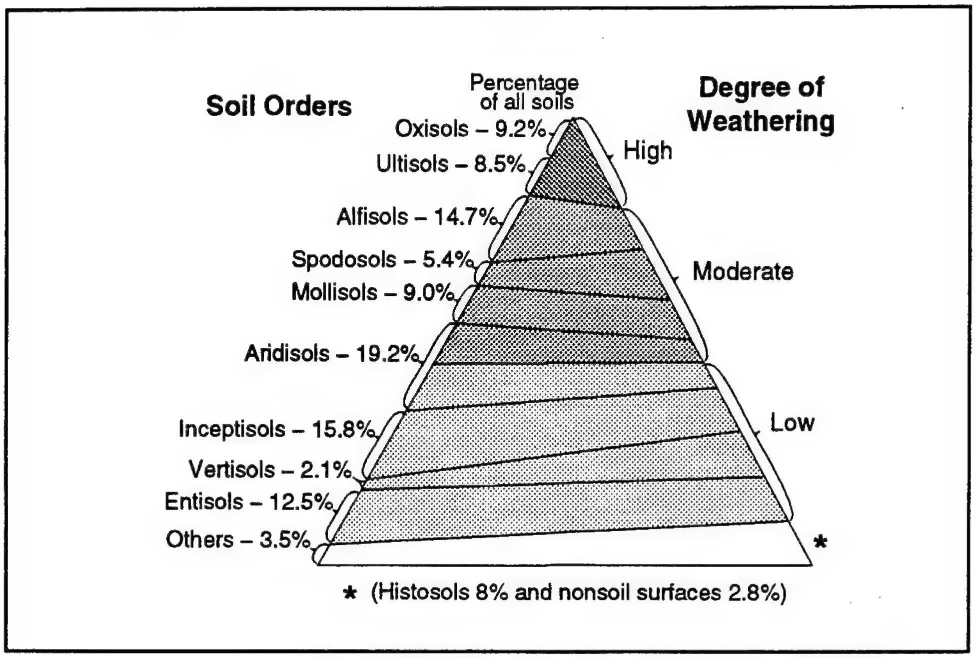


Figure 27. General relationship between soil orders and weathering. (After Steila (1976))

following discussion below is restricted to the hydrologic properties of soils, and to texture and composition of wetland soils.

Soil properties influence the ratio of infiltration to overland flow. **Infiltration rate** is the rate at which rain water enters a soil. **Transmission rate** is the rate at which water moves through the soil. Infiltration and transmission rates vary widely and depend on soil composition, moisture content, permeability, land use, land cover, and intensity and duration of rainfall. Soils are commonly layered so that transmission rates vary with depth. When the rate of precipitation exceeds the rate of infiltration, overland flow (runoff) occurs. In terms of runoff potential, the NRCS recognizes four **hydrologic soil groups**: (a) low runoff potential--thick, sandy to gravelly soils having high infiltration and transmission rates even when thoroughly wetted; (b) moderate to low runoff potential--moderate to thick, silty to sandy soils which have moderate infiltration and transmission rates when thoroughly wetted; (c) moderate to high runoff potential--silty and clayey soils which have moderate to low infiltration and transmission rates when thoroughly wetted: these soils commonly contain a layer that impedes downward movement of water; (d) high runoff potential--soils which have low infiltration rates when thoroughly wetted; these soils generally contain considerable quantities of clays with high swelling potential, have a permanent high water table, contain a clay pan or a clay layer near the surface, or are thin soils underlain by nearly impervious material. The NRCS has determined the hydrologic group classification for more than 13,000 soil types in the U.S and are listed in SCS (1985) or are available from the county and state soil scientists.

Infiltration and transmission rates in soil are influenced by land use and land cover as well as by soil composition. The NRCS uses a combination of

hydrologic soil groups and land use/land cover types to derive a hydrologic soil curve number (CN). The CN is an index of the runoff that will occur from a storm rainfall event and is commonly used to estimate surface water outflow for ungaged watersheds. CN's are also useful for predicting how changes in land use and land cover will affect the landscape's cycle of rainfall and runoff. A summary of CN's for hydrologic soil groups under various land use conditions is presented in Table 12. The use of CN's to estimate runoff volumes are discussed in more detail in the section entitled Overland flow.

A fundamental measure of soil hydrology is soil moisture potential. **Specific yield** is the ratio of the volume that drains from saturated sediment or soil under the force of gravity to the total volume of sediment or soil. **Specific retention** is the ratio of the volume of water that sediment or soil can retain against the force of gravity to the total sediment/soil volume. Specific yield together with specific retention equals total porosity. Specific retention generally increases with decreasing grain size such that clay soils may have a porosity of 50 percent and a specific retention of 48 percent. Table 17 lists specific yields, in percent, for a number of soil/sediment types.

Table 17
Specific Yields for Sediments, in Percent

Sediment Grain Size	Maximum	Minimum	Average
Clay	5	0	2
Sandy clay	12	3	7
Silt	19	3	18
Fine sand	28	10	21
Medium sand	32	15	26
Coarse sand	35	20	27
Gravelly sand	35	20	25
Fine gravel	35	21	25
Medium gravel	26	13	23
Coarse gravel	26	12	22

After Fetter (1988).

Another fundamental measure of soil hydrology is **field capacity** which is the maximum amount of water that an unsaturated soil can hold against the force of gravity, and is time dependent. Soils differ in their field capacities: fine sands hold ~9.1 cm (3.6 in.) depth per meter (3.3 ft) depth of soil, sandy loams hold ~13.5 cm (5.4 in.), and silty loams hold ~18 cm (7.2 in.). Loss of soil storage occurs if, over a period, ET exceeds precipitation. Under conditions in which soil moisture is less than field capacity, actual ET is less than potential ET. The climatic water budget of a landscape can be monitored

by evaluating the relationship between precipitation, actual, and potential ET (Figure 28). Landscape water budgets are discussed in the section entitled Regional water budget.

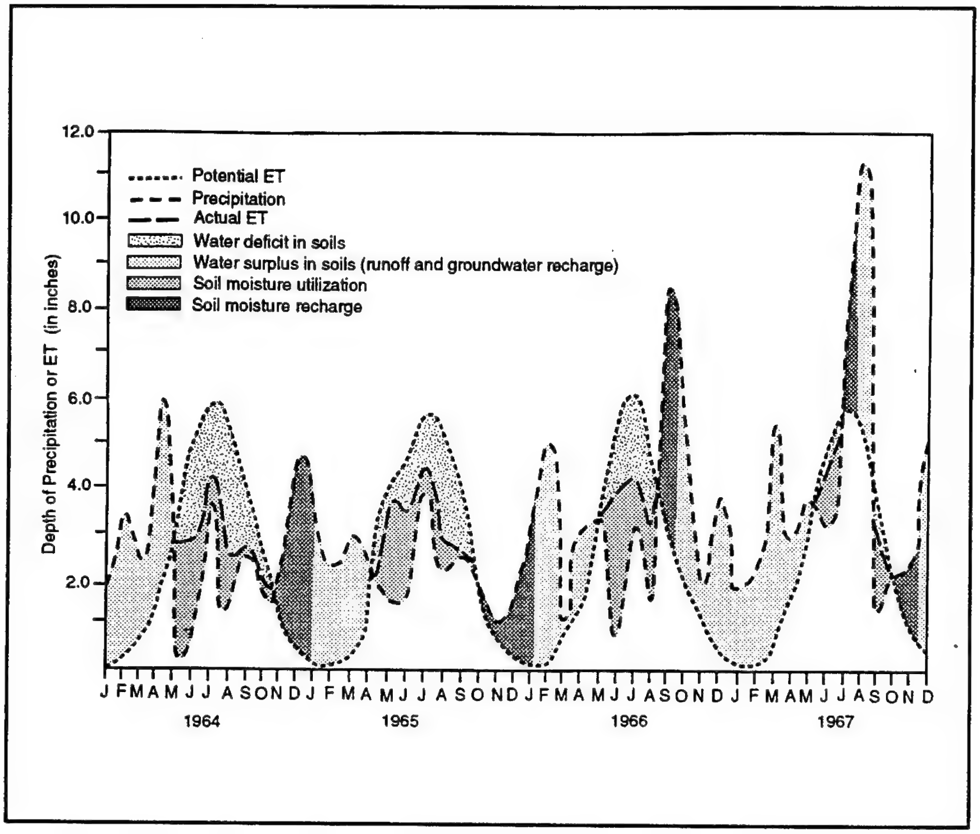


Figure 28. Monthly water budget for Wilmington, Delaware, region. (After Mather (1978))

Two principal types of soils occur in wetlands: the mineral soils and peat. Groundwater flow in mineral substrates is fairly well understood. The fibrous texture, continuous decomposition with burial, and widespread occurrence of macro pores, however, makes characterization of peat hydrology most difficult. For example, differences in vertical and horizontal conductivities in peat are reported to be large (Chason and Siegel 1986). In peats, hydraulic conductivities of the upper, partially decomposed **acrotelm** are generally assumed to greatly exceed the lower, more decomposed **catotelm** (Verry and Boelter 1978; Ingram 1983). Chasson and Siegel (1986) demonstrate that this is not always the case and attribute relatively high conductivities at depth to macropores associated with wood and rootlets.

Wetland soils are characteristically histosols (containing 20 to 30 percent organic material by weight), although mineral soils such as aquic inceptosols, entisols, ultisols, and even mollisols commonly underlie wetlands (Table 16). **Aquic soils** are those that are subject to continuous saturation or ponding of water for more than 2 weeks during the growing season. **Hydric** is a general term that denotes saturated, flooded, or ponded conditions during the growing

season such that anaerobic conditions develop in the upper soil horizon. A list of hydric soils found in wetlands has been compiled by the SCS (1987).

Saturated conditions in soils usually result in the following physical and chemical changes: (a) upon saturation, the rate of oxygen consumption, particularly by microorganisms, is high and oxygen replacement by diffusion through the liquid medium is low so that oxygen is soon depleted and reduction reactions quickly become the dominant chemical process; (b) percolation downward of water and dissolved soil constituents is restricted because of high water table; and (c) the heat capacity of soil is increased so that soils tend to be cooler in the spring and warmer in the fall than surrounding, unsaturated soils (Buol and Robertus 1988).

The dark or black color of most wetland soils is the result of organic matter, and indicates poorly drained conditions in which decomposition of organic matter is impeded by lack of oxygen. In the absence of organic matter, iron oxides determine the color of most soils. Reduced iron has a bluish and greenish gray color. **Gleyed soils** are the products of prolonged periods of saturation during which little water movement occurs through the soil, thereby preventing removal of reduced iron. Gleyed soils are generally associated with an aquitards (an impermeable zone). Red and yellow colors in soils are indicators of oxidized iron and hence aerobic conditions. **Mottled soils** result from the segregation of oxidized and reduced iron into zones as the result of different redox potentials, thus resulting in the red, yellow, and gray mottled zones. Mottling is common in soils in and near wetlands and generally indicates periodic water table fluctuations.

Buol and Robertus (1988) define four hydrogeomorphic settings in which distinct hydric soils develop: (a) wetlands (such as pocosins) on broad interstream divides or in raised bogs which produce nutrient-poor, histic soils; (b) riverine wetlands and depressional wetlands of floodplains which produce soils that are more diverse than on interstream divides, and are commonly quite fertile because they receive appreciable surface runoff; (c) depressional wetlands which produce soils that are rich in expandable clays in the B or C horizons and therefore have restricted rates of percolation in the subsoil; and (d) fringe wetlands which are subject to a wide range of inundation conditions by fresh, brackish, marine, or hypersaline water, and produce soils that are difficult to generalize.

Geologic processes

Climatic, gravitational, and hydrologic forces transform and reshape earth material. Interactions of force and resistance manifest themselves through the processes of weathering, erosion, transport, and sedimentation. Typically, sediments are produced in uplands, conveyed by overland flow to valleys where they are temporarily stored, and eventually transported via streams to lowland basins where they are deposited.

Weathering. Because many rock types formed under pressures and temperatures far different from earth surface conditions, they are in disequilibrium and subject to weathering. In addition to parent rock composition, the degree and intensity of weathering is a function of climate, topography, and time (Figure 29). Weathering begins in the shallow subsurface and results from interaction of rock with groundwater. Weather processes continue as rock and sediment are brought to the Earth's surface where they interact with surface water and the atmosphere (i.e., precipitation, temperature, wind). Weathering is a three-fold process: mechanical, chemical, and biological. Mechanical weathering processes include thermal expansion and contraction, frost wedging, and crystal growth (Bloom 1991). Chemical weathering, which is generally the dominant process, represents the transformation of minerals by water as they are exhumed, eroded, and transported through the landscape. Chemical weathering processes, which are enhanced by wet and warm conditions, include oxidation, hydrolysis, and transformation of silicate minerals generally to clays. Biological weathering processes include chelation by plant roots and microbial activity which greatly enhances rates of chemical reactions. Bacterial activity is increasingly recognized as a major component in rock weathering. Press and Sevier (1986), Twidale (1990), and Bloom (1991) provide more detailed discussions of weathering.

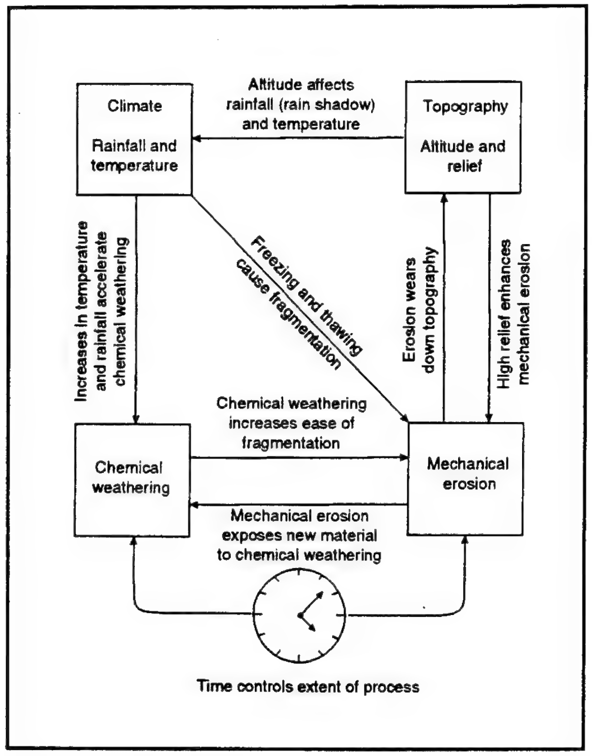


Figure 29. Interrelationships among major factors that control weathering and erosion. (After Press and Sevier (1986))

Erosion. Soil erosion, soil loss, sediment yield, and denudation (geologic erosion) have distinct meanings, although each represent part or all of the process of removal of material from a landscape and subsequent lowering. Soil erosion is the amount of soil removed by rain drop detachment and runoff. Soil loss is the amount of soil moved off a particular area. Sediment yield is the quantity of sediment delivered to or through a certain point in the landscape, and denudation is the long-term ground loss and subsequent lowering of a landscape.

Empirical equations and models, which are generally based on controlled field measurements, are commonly used to measure **soil erosion and loss**

(EPA 1992). The Universal Soil Loss Equation (USLE) is the best known of these equations:

$$A = R\,K\,L\,S\,C\,P$$

where

R = rainfall-runoff

K = soil erosivity

L = slope length

S = steepness

C = land cover

P = land management practices

These six factors are the critical parameters for estimating soil erosion. Note that the USLE's soil erosivity factor, K, accounts for soil erosion, and A accounts for soil loss. The USLE was derived by the Agricultural Research Service (ARS) from statistical analysis of 10,000 plot-years of data from natural runoff plots and the equivalent of 1,000 to 2,000 plot-years of data from rainfall simulators (Wischmeier and Smith 1978; Fan 1988). The USLE has been criticized for not adequately predicting soil loss in forested areas. More in depth discussions, along with tables and graphs for determining the six soil loss parameters, are available in Mather (1978) and Wischmeier and Smith (1978); Mitchell and Bubenzer (1980) provide an especially lucid account of the USLE.

The most widely used technique for estimating sediment yield is measuring transported sediment volumes in streams and rivers and dividing by the catchment area. Sediment volumes in streams are calculated using either depth-integrating or point-integrating suspended sediment samplers. Methods for estimating sediment volumes from stream gaging stations are discussed in the section entitled Transport.

The second most widely used technique for measuring **sediment yield** is estimating sedimentation rates in reservoirs. Analysis begins by evaluating the thickness of sediment which has been deposited over a given length of time. Methods for evaluating sediment accumulation rates are discussed in the section entitled Storage. Once the thickness of sediment accumulated per unit time has been established, the area over which sediment accumulation has occurred is determined, and the volume of sediment per unit time is calculated by multiplying the thickness times the area over which sediments were deposited. Depressional wetlands with no outlets tend to retain nearly all sediment that is transported into them and therefore can be used to measure sediment yield.

Denudation or **geologic erosion** is defined to be the mean ground loss from a watershed. Geologic erosion (denudation) rates from naturally

vegetated areas are commonly less than 2 in./1,000 years (Table 18). Acceleration of erosion rates by human activities ranges from 2 to 3 times with moderate land use to nearly 10 times with intense land use (Saunders and Young 1983; Hooke 1994). Construction sites commonly have erosion rates far exceeding 10 times geological erosion rates (Vanoni 1975). However, once completed, urban settings with their abundance of impervious surfaces (roofs and pavements), commonly have relatively low erosion rates. In such areas, however, chemical loading and the ratio of runoff to rainfall are quite high.

Table 18
Rates of Geologic Erosion (in./1,000 years)

Climate	Relief	Typical range
Temperate continental	Normal	0.4-4.0
	Steep	4.0-8.0
Rain forest	Normal	0.4-4.0
	Steep	4.0-40.0
Arid	Variable	0.4-?
Semiarid	Normal	4.0-40.0
Polar/mountainous	Steep	4.0-40.0
Glacial, ice sheet	Normal	2.0-8.0
Glacial, valley glaciers	Steep	40.0-200.0
Any climate	Badlands	40.0-40,000

Source: modified and simplified from Saunders and Young (1983), after Press and Sevier (1986).

Transport. Sediment may be transported by water, wind, or simply by the force of gravity. The discussion here is limited to sediments transported by water. In some regions of the United States, especially coastal zones and the Southwest, wind is a significant transporting agent. In regions of high relief, gravitational transport mechanisms such as slumps, earthflows, and debris slides are significant landscape processes. Ice and snow are an important element in erosion and sediment transport in the northern United States For example, ice push along the banks of northern wetlands is currently responsible for displacement of significant volumes of sediment (Woo and Winter 1993). Ritter (1986), Bloom (1991), and Easterbrook (1993) provide introductions to the role of wind, gravity, and ice in landscape evolution.

For analytical purposes, water transported sediment (sediment load) is subdivided into dissolved, suspended, and bed load. **Dissolved load** includes all ions of weathered material; **suspended load** is generally fine material transported in the main body of flow and is kept afloat by the upward momentum in turbulent eddies; and **bed load** is generally coarser material that moves by rolling, sliding, or saltation along the bed of a stream. The relative

importance of these transport mechanisms depends upon the geologic setting, relief, climate, land use, and land cover characteristics. Sediment transport is a complex process, and the division made between suspended load and bed load is arbitrary and depends on flow velocity and shearing stress. The volume of sediment that flowing water is able to transport is its **capacity**. Although a stream's ability to carry sediment is to some degree a function of the channel width and depth, capacity is primarily governed by discharge rate (Figure 30).

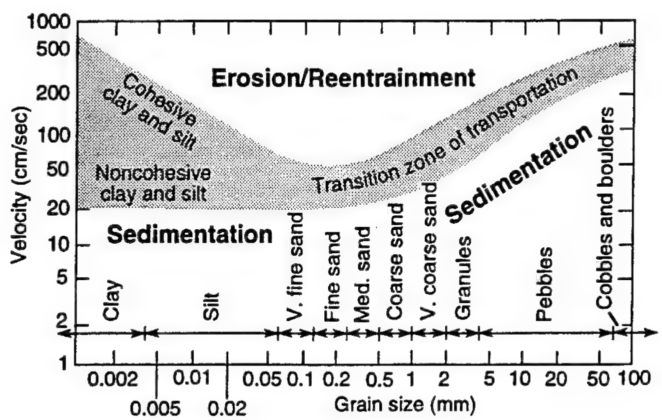


Figure 30. General relationship between sediment size, water velocity, and deposition and transport. (After Press and Sevier (1986))

In Figure 30, measurements were made on a flat, granular bed of quartz sand. For a specific grain size, the lower limit of the gray zone demarcates the velocity at which all particles of that size will fall to the bed. The upper limit of the gray zone in Figure 30 demarcates the velocity at which all particles of that size continue to be reentrained from the bed. The gray zone is broad because many of the physical properties of water and sediment grains are not accounted for by grain size and water velocity alone. The gray zone in the silt and clay size portion is especially broad because of the electrostatic forces binding clay minerals.

Dissolved load is measured by chemical analysis of water samples. Suspended sediment volumes are generally measured using a depth-integrating or point-integrating sampler during a specified time interval (Vanoni 1975; USGS 1977; Federal Inter-Agency Sedimentation Project 1986). The volume of sample and information on discharge are used to calculate suspended sediment load volume. A significant quantity of sediment is transported during peak floods, when hand sampling is generally not possible. To overcome this, pumping samplers that can be activated by a rise in water stage, are available (USGS 1977). Once sediment load measurements have been made at a variety of discharge rates, sediment yield may be evaluated by correlating sediment load volumes and stream velocities. This is accomplished by plotting on log-log or semilog scales the sediment volume versus stream discharge rate. This

provides a basis for a **sediment rating curve**. A sediment rating curve, by using interpolation and extrapolation, provides a basis for predicting sediment yield from a given stream discharge rate without direct measurement of sediment volume. A flow duration curve, which is a summary of discharge rates over time, can be used to determine longer-term sediment yields. There are several sources of error associated with evaluation of sediment yield from stream sediment volume measurements: many records only account for suspended load and ignore dissolved and bedload, and many studies do not include extreme events during which a significant proportion of sediment, particularly bedload, is transported through the system. Detailed discussions of measuring stream sediment volumes are provided by Vanoni (1975) and USGS (1977).

Storage. For reasons not fully understood, the volume of sediment transported out of watersheds is less, and commonly much less, than sediment eroded from the land surface of the watershed. Meade, Yuzyk, and Day (1990) estimate that 70 to 80 percent of sediment eroded across the United States annually is stored in hillslopes and floodplains (only a fraction of which are wetlands) with about 10 percent trapped in reservoirs and 10 percent being delivered to the oceans (Hajic and Smith in press). The disparity between sediment erosion and sediment yield is greater for larger watersheds reflecting the greater number of intermediate storage components.

Sediment storage may be temporary or long-term. Temporary storage components of a landscape are generally controlled by intensity, duration, frequency, and timing of meteorologic events such as rain and wind storms, rapid snowmelt, and hurricanes. Stream valleys typically store sediments eroded from uplands. Storage in stream valleys may be temporary, and sediment residence times is a function of watershed relief, stream channel gradient, upland soil characteristics, and magnitude and frequency of precipitation events. Lakes and ponds tend to be sites of longer-term storage. Because wetlands typically occur in some form of depression and are sites of vegetal accumulation, they are commonly sediment storage locations. In fact, wetlands that occupy at least 1 percent of the watershed area and are capable of storing more than 10 percent of their average annual inflow commonly trap more than 85 percent of incoming sediment (Dendy and Bolton 1976).

In general, the capacity of water to displace sediment increases with increasing flow velocity and water depth. Figure 30 demonstrates that water velocities required for reentrainment of sediment are considerably greater than water velocities capable of transporting suspended sediment of the same grain size. The increase in the disparity between water velocities capable of transport to those of reentrainment in the clay-size range reflects the strong electrostatic cohesive forces of clay minerals. The difference in transport and reentrainment velocities may explain why few wetlands export more inorganic sediment than they import.

As mentioned previously, the volume and size of sediment transported is largely a function of water flow rate. Similarly, specific water velocities and sediment grain size combinations produce particular bedforms (Figure 31).

As these bedforms accrete, they retain characteristic features in cross section, known as sedimentary structures, that reflect hydrodynamic conditions at the time of deposition. Cross-bedding is a commonly observed sedimentary structure (Figure 32). Bedding geometry and size, sediment grain size distribution, and sedimentary structures are used to decipher the depositional history of sedimentary environments. Selley (1988) and Chamley (1990) provide more thorough reviews of sedimentologic principles and analysis.

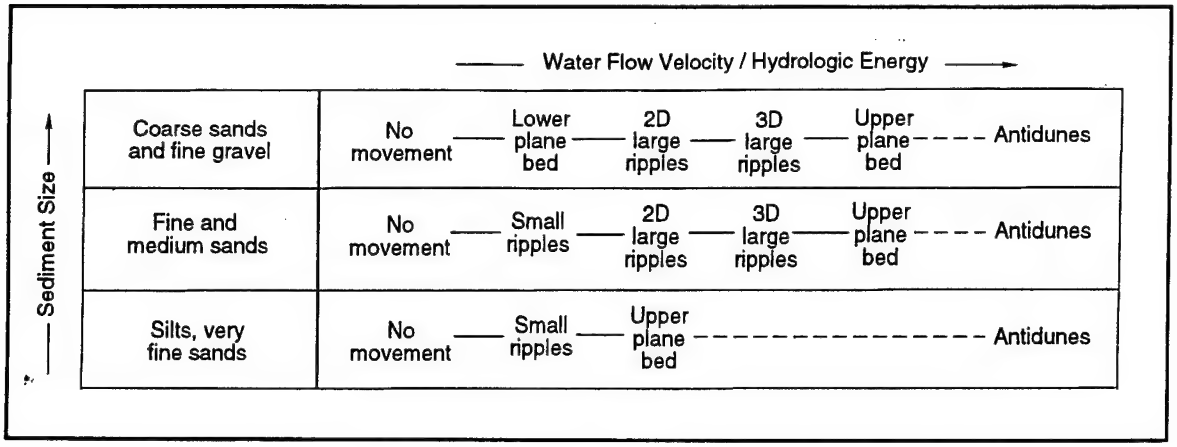
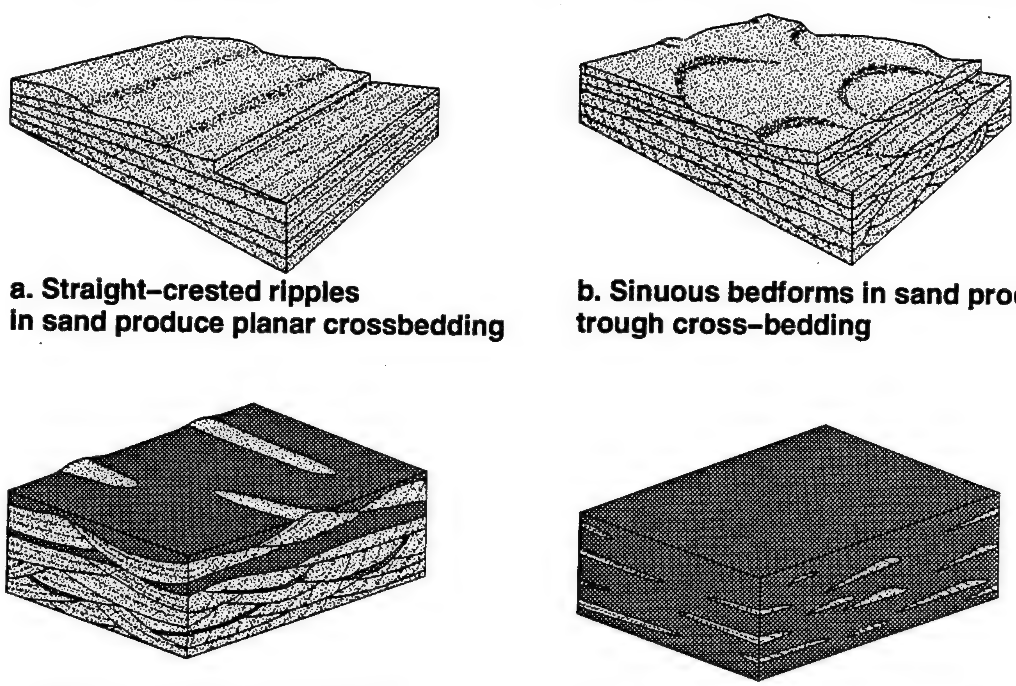


Figure 31. Sequence of bedforms produced at different water velocities. (After Press and Sevier (1986))

Several methods are available to measure the age of sediments and rates of sediment accumulation. Carbon 14 (^{14}C) radioactive isotope dating is the most common method for measuring the sediment accumulation rates at the millennia scale (Mook and Van de Plassche 1986). Millennial scale sediment accretion rate estimates provide a basis for interpretation of landscape history and, when compared to more recent rates, provide insight to the equilibrium state of the landscape. Amino acid racemization dating methods are used to resolve accretion rates on the decadal to millennial scale. Artifact horizons generally yield accretion rates on the decadal to millennial scale. Cesium 137 (^{137}Ce) and Lead 210 (^{210}Pb) radioactive isotope dating techniques yield accretion rates on the decadal to centennial scale (DeLaune, Smith, and Patrick 1986; Bricker-Urso et al. 1989; Delaune et al. 1989; Lynch et al. 1989). Thermoluminesence dating techniques are used to resolve accretion rates on the decadal to centennial scale. Artificial marker horizon dating techniques which use filter paper, feldspar powder, brick powder, and rare earth elements as marker horizons, provide information on accretion rates at a seasonal to annual scale (Cahoon and Turner 1989; Knaus and van Gent 1989; Reed 1989; Wood, Kelley, and Belknap 1989). Short-term accretion rates can also be measured using sediment traps. A simple trap consists of a polyethylene jar secured to a concrete slab. Easterbrook (1993) provides a more in depth review of methods for dating landscapes.

Sediment routing and budgeting. A principal cascading system within landscapes is the weathering, transport, and storage of sediment within the system. **Sediment routing** describes the path of sediment as it moves through



a. Straight-crested ripples in sand produce planar crossbedding

b. Sinuous bedforms in sand produce trough cross-bedding

c. Mixtures of sand and mud in which sand is the dominant component, produce flaser bedding

d. Mixtures of sand and mud in which mud is the dominant component produce lenticular bedding.

Figure 32. Bedforms and associated sedimentary structures

the landscape system. A **sediment budget** quantitatively describes the rates of production, transport, and discharge of detritus. Sediment budgeting and routing are a conceptual simplification of the interaction of processes that convey debris through the watershed. Sediment routing and budgeting estimates require recognition and quantification of (a) sediment sources, (b) weathering processes, (c) erosion processes, (d) transport processes, (e) quantity of transported material, (f) types and rates of material transformation, (g) timing of material transfers and transformations, and (h) storage elements.

Evaluation of sediment routing and budgeting requires the use of soils, topographic, geologic, and land cover information as well as aerial photography. The advice of geologists, soil scientists, and hydrologists who are familiar with the landscape can be most helpful with these estimates. Sediment routing and budgeting can be estimated using the following steps:

a. A grid is overlain on a base map, and the following procedure (steps 2 through 5) is carried out at each grid intersection. The size of the overlay grid depends on the size of the landscape to be analyzed and the level of detail sought. A minimum of 50 grid cells is recommended.

b. At each grid intersection, the landscape should be identified as either a sediment production, transportation, or storage element. Recognition of areas producing sediment requires recognition of dominant hillslope processes, i.e., rain splash, sheet wash, rill formation, and soil creep. The difference between temporary (<50 years) and long-term storage should be made. Determination of residence times in short-term storage components is difficult because durations are commonly many times longer than the period of observation, or even human life span. Sedimentologists or geomorphologists familiar with the landscape can be most helpful with these estimates. Observation on the relative intensity of geomorphic processes acting on an area can provide information about residence times. Residence times in low-order streams is generally less than in higher-order streams.

c. The mechanisms which transport sediment within the system should be distinguished, and the principal routes of the sediment transport through the landscape should be mapped.

d. For sediment budgeting, rates of erosion, transport, and deposition are estimated at each grid line intersection. Erosion rates can be derived from sediment volume estimates made at stream gaging stations (section entitled Transport) or from soil loss equations (section entitled Erosion). Transport rates through stream valleys are more difficult to quantify because there have been few studies that have monitored the movement of marked sediment through stream valleys. Judgements based on the relative intensity of the transporting agents and frequency of recurrence of transport events is the most practical method for estimating sediment transport rates. Sedimentation rates can be determined by isotopic or artificial marker horizon techniques, from sediment traps, or by monitoring sediment inflow and outflow through storage components.

e. The various types of components as well as rates of erosion, transport, and sedimentation should be recorded on a map and preferably entered into a GIS. Many GIS programs are capable of simulating sediment routing using the information described above.

Special attention should be given to high-intensity storms and their frequency. These storms should be evaluated in terms of their capacity to transport sediment through the system and move material into and out of areas of temporary storage.

From the sediment routing/budgeting map, it should be possible to determine which parts of the system are energy-limited and which parts are material-limited, and which landscape components exert the most control on flow of material through the landscape. **Energy-limited** landscapes (or landforms) are those in which there is more sediment than processes capable of transporting or transforming available material. **Material-limited** landscapes are those in which process intensities and durations are more than enough to transport and transform available sediments. Energy-limited landscapes are

typically depositional whereas material-limited landscapes are erosional environments.

Geomorphology

Landscapes are derived from the interaction between driving forces and resistance. Driving forces include climate, gravity, hydrology; resistance is provided by the geologic framework; and the links between these two components are the landscape forming processes (Ritter 1986). Landscape forming processes include weathering, erosion, transport, and sedimentation. In general, processes are either exogenic or endogenic. **Exogenic processes** act near the Earth's surface and are normally driven by gravity and atmospheric forces. **Endogenic processes**, although they occur at the surface, are driven by geothermal energy deep inside the Earth. The effectiveness of processes on resistance depends upon the frequency, intensity, and timing of the forces which act upon the landscape, and the length of time that a particular set of forces has been active.

This section begins by describing quantitative methods for analyzing the relationship between landscape form (morphometry) and hydrologic response. Next, equilibrium states and landscape evolution are discussed. Then the magnitude and frequency of events which perform geomorphic work are discussed.

Watershed morphometry. Drainage basins are the fundamental unit of geomorphology and are a principal morphological system within landscapes. A great deal of research has been carried out on their geometric characteristics including stream network hierarchies, and quantification of drainage texture, pattern, shape, and relief (Patton 1988). Basin morphometry includes evaluating the interrelationships between basin form, stream network characteristics, and resulting water and sediment yield.

Geomorphic features are generally linear, areal, and relief aspects of a watershed. Linear aspects of a basin are those concerned with stream channels. If attention is paid to interconnections of stream channels, it is possible to devise a scheme of **stream ordering**. A first-order stream is one which does not possess tributaries, a second-order stream is formed by the junction of two first-order streams, a third-order stream by the junction of two second-order segments, and so on. The **bifurcation ratio** is the ratio of the number of streams within a watershed of a given order to the number of streams of the next highest order. In general, basins with low bifurcation ratios produce hydrographs with marked discharge peaks, whereas those with low ratios give rise to low peaks over longer time periods. This makes intuitive sense: drainage basins with high bifurcation ratios contain a larger number of tributaries so that a landscape is capable of concentrating overland flow into stream channels for rapid transport out of the watershed.

One of the most useful geomorphic measures is drainage density which reflects the competing processes of overland flow and infiltration:

drainage density = total stream length/area of drainage basin

This is, to some extent, a measure of the evolutionary development of a landscape such that lower ratio values imply that a watershed is in early stages of geomorphic development and can be expected to change over time. Drainage density is also a function of relief, climate, soils, and geology. Basins of high relief tend to be dominated by overland flow and therefore develop high drainage network densities relative to lower relief terrains with similar surface conditions. Drainage densities tend to increase from arid to semiarid environments, decrease to the lowest drainage densities in humid temperate regions, and increase in the tropics (Patton 1988). Within a particular climatic zone, the magnitude, frequency, and timing of precipitation events, which controls the proportion of overland flow, is a critical factor in determining drainage network density. In spite of the above observations, no universal model has been developed which makes use of this measure. Generalizations may be difficult because development of drainage density within a basin requires geologic time that is far longer than periods of climatic stability (Patton 1988).

The importance of basin relief as a hydrologic parameter has long been recognized. With increasing relief, steeper hillslopes, and higher stream gradients, the ratio of runoff to infiltration increases and time of concentration of runoff decreases, thereby increasing flood peaks. Two useful measures of relief for evaluating the hydrology of a watershed are the relief ratio and the ruggedness number (Patton 1988). The **relief ratio** is the basin relief divided by the length of the long axis of the basin. It is intuitively obvious that a basin of high relief and short valley axis rapidly delivers runoff to the valley head, whereas a low relief basin with an extended valley axis delivers runoff to the valley head over a more protracted period of time. It follows then that basins with high relief ratios tend to have high flood peaks. The **ruggedness number** is the product of drainage density multiplied by basin relief. Basins with high ruggedness numbers tend to have high peak flows. It is of note that highly dissected basins of low relief can have ruggedness values similar to moderately dissected basins of high relief.

The hydrograph signature and sediment yield characteristics of a landscape are also controlled by the overall basin shape. In particular, rotund-shaped basins with low bifurcation ratios and nearly equal stream path lengths tend to have high flood peaks because surface water travel times to the base of the watershed are nearly equal across the basin. On the other hand, elongate basins with high bifurcation ratios and unequal stream path lengths tend to have lower flood peaks but sustained flow, because travel times to the base of the watershed vary (Strahler 1964). The overall shape of a watershed can be evaluated with the elongation ratio

elongation ratio = D/L

where

D = diameter of a circle having the same area as the drainage basin

L = the longest axis of the watershed

It is of note that watersheds whose form is controlled by linear features such as lineaments, faults, and folds tend to have low elongation ratios.

USGS (1977), Chorley, Schumm, and Sugden (1985), and Ritter (1986) provide more detailed discussions on quantitatively analyzing the relationships between watershed form and function.

Equilibrium states. Dynamic equilibrium implies that a landscape system is seldom, if ever, characterized by exact equilibrium, but rather has the tendency to gravitate toward a state of maximum efficiency (Chorley 1962). Dynamic equilibrium is the ongoing adjustments of morphological and cascading systems within landscapes to oscillations in input of energy and materials. The form and function of landscape features are generally controlled by events that recur in a periodic fashion. For example, the channel shape and meander size of rivers is related to flows at bankfull stage. These flows, which recur every year or two, rather than 50 or 100 year floods, exert an overriding influence on river channel and floodplain form and function. The relative importance of an event on landscapes can be measured in terms of the amount of material transported through the system (**geomorphic work**), and the degree of development of specific landscape features (**geomorphic effectiveness**). As work is done on landscapes, or as a landforms attain certain stages of development, systems reach levels of inefficiency such that threshold conditions are surpassed and the systems rapidly adjust toward new equilibrium states.

Fundamental changes brought about by processes outside of the landscape are known as **extrinsic thresholds**. For example, during a flood, water velocities in a floodplain may be capable of transporting sediment into the system (Figure 30). If water velocities continue to increase, sediments are reentrained and erosion commences. **Intrinsic thresholds** refer to changes that take place in landscapes even though external forces remain relatively constant. Intrinsic threshold conditions develop in response to gradual, often imperceptible changes within the system itself (Ritter 1986). Intrinsic thresholds are generally associated with slope failure in which the strength of soil, sediment, or rock deteriorates to a critical point at which landslide, slumping, or rockfall occurs. The transition from minerotrophic to umbrotrophic conditions in a raised bog is also an intrinsic threshold.

Threshold conditions commonly initiate a series of reactions called complex response (Ritter 1986). A sequence of events occurs because not all components and processes of landscape systems are at the same equilibrium state at a given time. Complex adjustment to altered conditions involves a chain reaction of processes called process linkage (Ritter 1986). Process linkage operates on the domino principle such that changes that occur in one process or landform initiate responses in other, seemingly unrelated landscape components. Thus, a myriad of different processes can be affected by the response of a single threshold-inducing force (Ritter 1986). The concept of complex

adjustment and process linkage provide an explanation for seemingly random changes that have been noted in wetland landscapes (Niering 1987).

Geomorphic thresholds consist of three types: step, ramp, and transient. Step thresholds involve abrupt changes in which form and (or) processes are modified for significant periods. An example would be meander cutoff and conversion of the former channel to an oxbow lake. Ramp thresholds are those involving gradational, but significant and long-lasting changes in landforms and (or) functions. An example would be the change from minerotrophic to umbrotrophic conditions in a raised bog. Transient thresholds involve rapid departures to a different landforms or functions, but rapid return to prethreshold conditions. An example would be reestablishment of plant communities in a tidal marsh after a hurricane. All types of thresholds are relative terms, and what encompasses normal deviations from the mean dynamic equilibrium state is, by in large, a function of the time scale of observation (Figure 5).

Magnitude-frequency analysis. Geomorphic processes generally do not act upon a landscape in a continuous fashion (Wolman and Miller 1960; Wolman and Gerson 1978). In fact, most geomorphic work is done within a small portion of a given period. For example, Meade and Parker (1985) demonstrate that approximately 90 percent of the annual suspended sediment budget in diverse streams was discharged over approximately 10 percent of the year, that is during peak flow periods caused by prolonged rains, snowmelt, and storms. In a typical river, suspended load and bedload may increase by as much as 1,000 fold during floods (Komar 1988).

Recurrence of events which induce threshold conditions in a landscape commonly exceeds the observation period and even human life span. A basic problem of magnitude-frequency analysis is the need to extrapolate for long time spans from a limited period of scientific observations. This raises the question, can space be substituted for time? If space is to be substituted for time in the study of magnitude-frequency relationships between geomorphic processes and form, two criteria must be met: (a) a homogeneous sample area (similar geology, tectonic setting, and climate), and (b) a sufficiently large sample area.

In magnitude-frequency analysis, climatic and geomorphic events should be differentiated. Climatic events are the forces driving the landscape development whereas geomorphic events are the landscape response (Kelsey 1982). In general, successive climatic events are independent of one another, whereas successive geomorphic events are more closely related. For example, the second of back-to-back thunderstorms of nearly equal intensity and duration operates on a different set of sediment storage and wetland vegetation conditions and therefore will have different geomorphic consequences than the first flood. Hence the capacity of a climatic event to perform geomorphic work is governed not only by the magnitude of the force or energy which it brings to bear on the landscape, but also by the frequency at which it recurs, the processes acting on the system during intervals between recurrences, and work performed during such intervals. Therefore, the recurrence interval of storms

of high intensity and duration may not be as critical to landscape evolution as is the recurrence high volume runoff events which could be induced by snow melt or consecutive moderate storms during periods of cool weather.

Geomorphic work in most landscapes, however, is associated with intense rainfall events and flooding. Therefore, the frequency of recurrence of flood-causing events merits special attention. Beard (1975) devised a quantitative scheme for the conterminous United States for predicting the probability of flash floods for a given area. A flash flood is defined as a damaging flood which occurs within 4 to 6 hr of the causative rainfall event. Using more than 2,900 stream flow stations that have records exceeding 20 years, Beard (1975) quantified the likelihood of occurrence of flash floods with the **Flash Flood Magnitude Index (FFMI)** which is the standard deviation (SD) of the logarithm of average annual maximum discharge (Figure 33). SD is a measure of the degree of variance of a group of measurements from its mean which. In the case of the FFMI, the degree of variation of the logarithm of individual maximum annual discharges from the logarithm of the mean maximum annual discharge. Therefore, the larger the FFMI, the greater the possibility of flash flooding and the greater the likelihood of major geomorphic change caused by floods (Kochel 1988). Other factors such as vegetation, lithology, and basin morphology are also important contributors to flood response (Beard 1975).

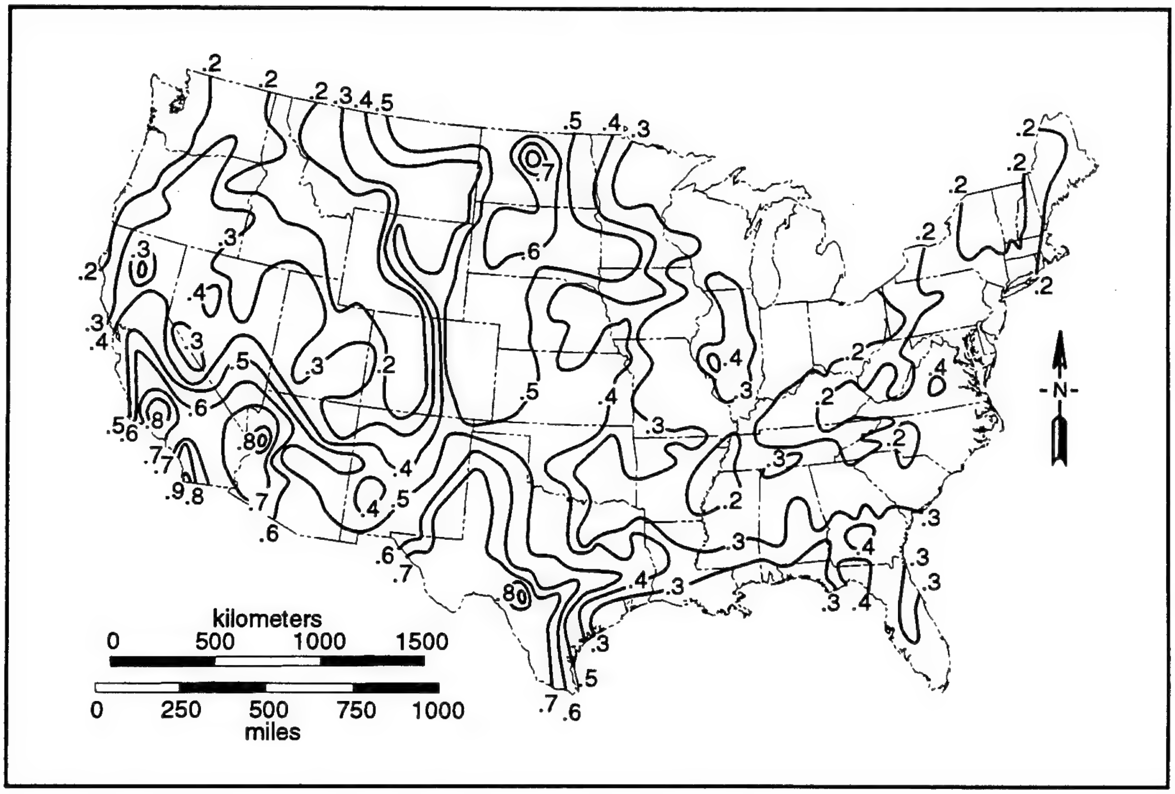


Figure 33. Distribution of the Flood Magnitude Index for the conterminous United States. (After Beard (1975) and Kochel (1988))

Magnitude-frequency analysis is also concerned with the rate at which a landscape reequilibrates relative to the frequency of climatic and geomorphic events that induce threshold conditions. Expressed graphically, changes in a system may all originate from the same base level if recovery rate is fast relative to frequency of disturbance (Figure 34a). If events occur so frequently that recovery from previous events is not complete (Figure 34b), the effect of any one event is determined in part by the magnitude and timing of past events. An intermediate alternative, and one representative of dynamic equilibrium, is a combination of system recovery and system influenced by past events (Figure 34c).

Landscape systems or landforms that continue to be influenced by previous conditions (generally the last glacial epoch) are known as **relict**. Relict landforms are those physical components of a landscape which have not had sufficient time for system recovery.

Hydrology

Hydrology is the most important determinant in the establishment, development, and maintenance of specific wetland types and wetland functions (Mitsch and Gosselink 1993). Even if a physiographic and geologic setting are favorable for the formation of a wetland, hydrologic conditions must be such that water will persist long enough for a wetland to form. Because wetlands are low relief, shallow water environments which are intermediate between aquatic and terrestrial environments, they are particularly sensitive to changes in patterns of water movement and storage. Changing hydrologic conditions directly modifies chemical and physical properties such as nutrient availability, degree of substrate anoxia, soil and water salinities, sediment budgets, and pH which in turn influence the biologic components of the system.

In terms of systems, hydrology is the major cascade in wetland landscapes and thereby controls the flow of energy and materials as well as the forms and processes of associated morphological systems (substrate, plant communities, water chemistry, etc.). A general schematic diagram showing the interrelationships between the elements of the hydrology cascade and associated morphological systems is presented in Figure 35.

Some generalizations can be made about the relationship of hydrology to wetland structure and function (Mitsch and Gosselink 1993):

a. Hydrology leads to a unique vegetation composition but can limit or enhance species richness.

b. Primary productivity in wetlands is enhanced by flowing conditions and a pulsing hydroperiod and is commonly depressed by stagnant conditions.

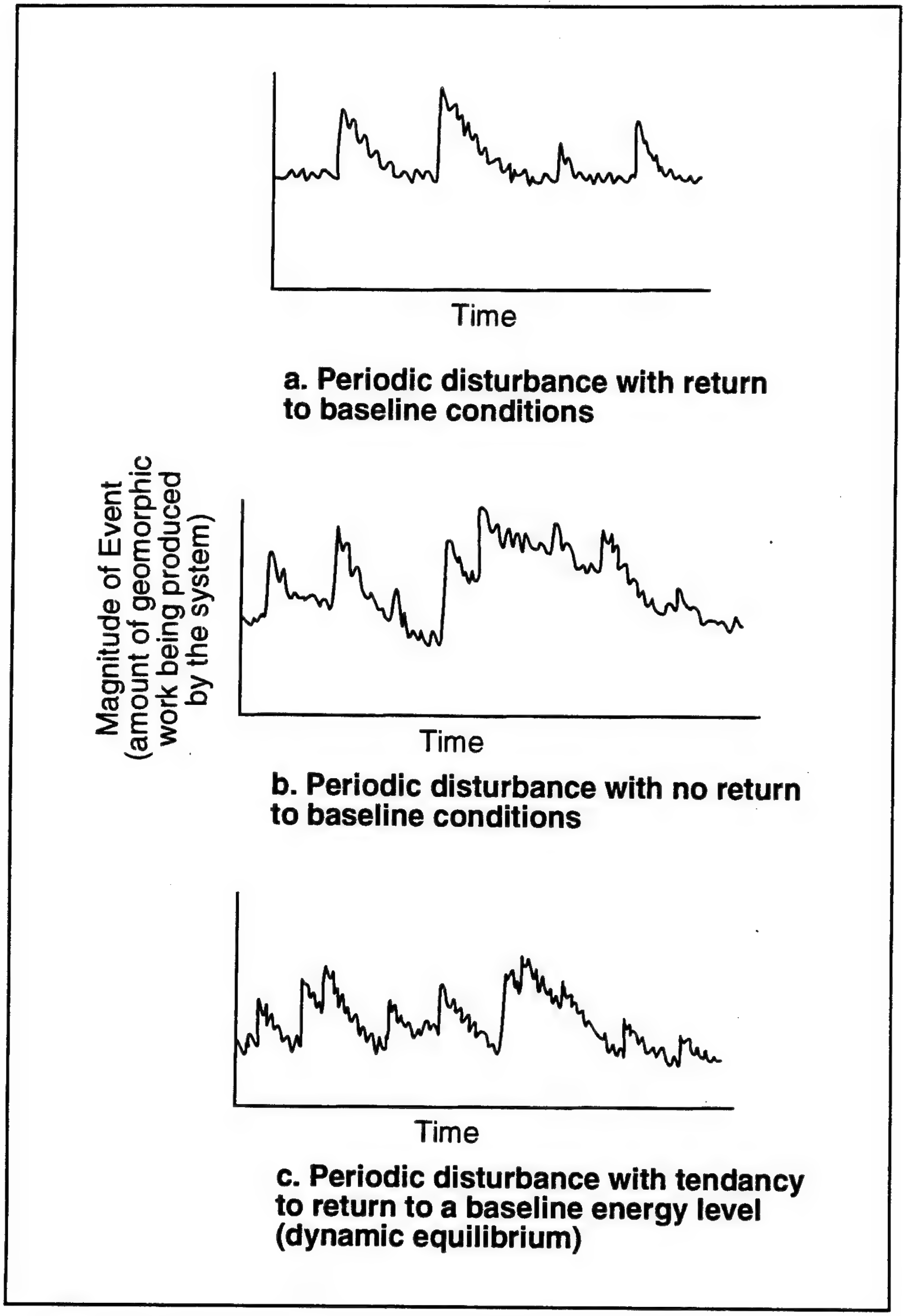


Figure 34. Examples of the relative effect of magnitude and frequency of geomorphic events and recovery rate on landscape equilibrium states. (After Kelsey (1982))

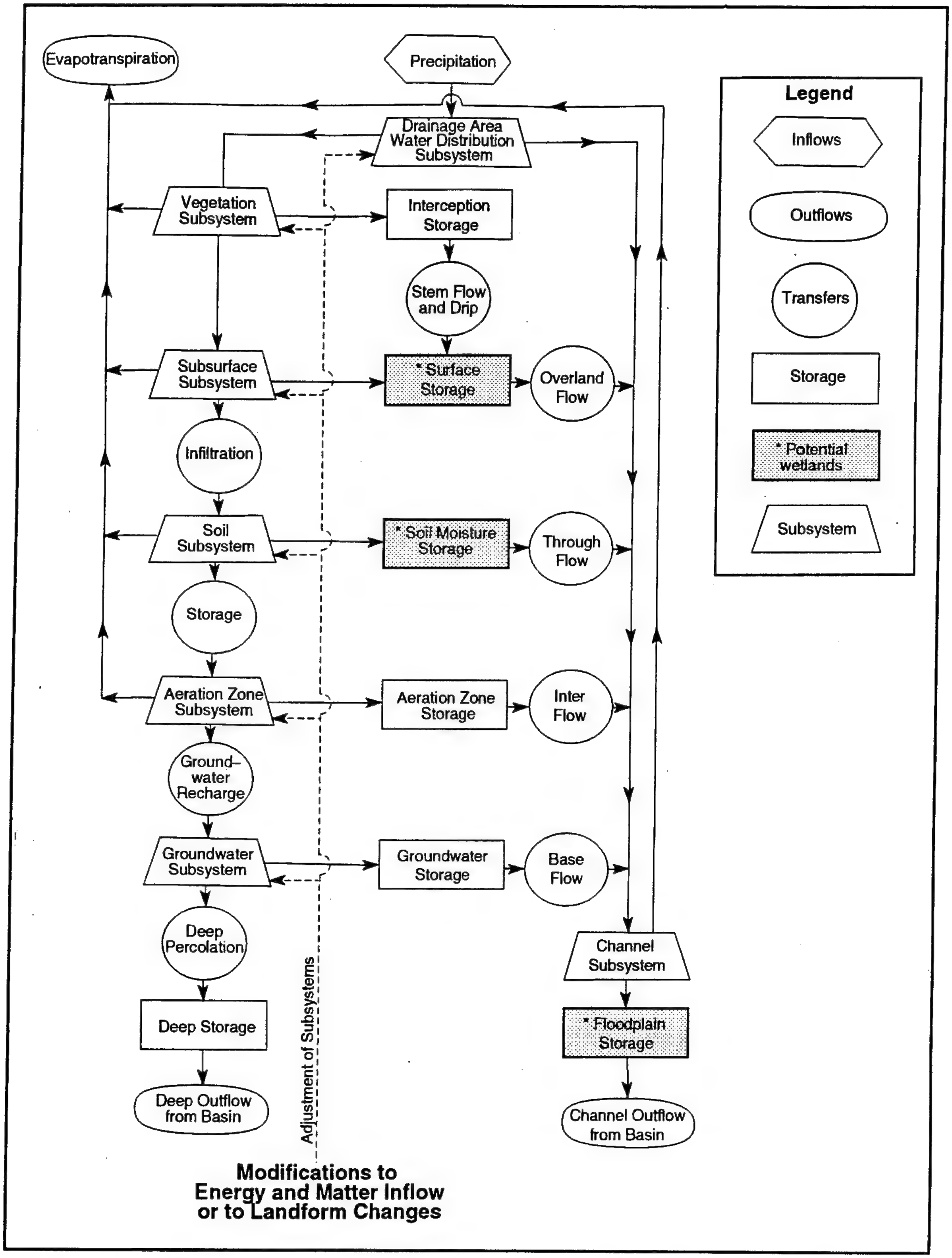


Figure 35. Schematic diagram showing the basic exchanges and storages involved in a basin hydrologic cycle. (After Chorley, Schumm and Sugden (1985))

c. Organic accumulation in wetlands is controlled by hydrology through its influence on primary productivity, decomposition rates, and export of particulate organic matter.

d. Nutrient cycling and nutrient availability are significantly influenced by hydrologic conditions.

Woo and Winter (1993) discussed the role of ice and permafrost in wetland hydrology. In northern portions of the United States Woo and Winter found that during early spring, surface ice and snow melt before soil frost so that melt water flows over the land surface with little interaction with the groundwater system. During summer and autumn, however, the groundwater system may play an integral role in wetland hydrology. Because seepage in early spring is minimal, widespread saturated conditions are common in the prairies of the Midwest, a region where annual evaporation exceeds precipitation (Figure 17).

This section on hydrology begins by describing potential hydrologic data sources. Next, water budgets and water budget calculation are discussed. Then groundwater and surface water and their interaction between landscapes and wetlands are discussed.

Hydrology data sources

A primary source of historic hydrologic information is the USGS's WATSTOR, and soon, NWIS II database management system (Table 10). Stream gage locations, stage levels, and flow rates are available for many streams in the United States through WATSTOR, and through USGS Water Data Reports published annually for each state. NASQAN, which is also stored in the WATSTOR database and available through the NAWDEX retrieval service (Table 10), is a stream water quality database maintained by the USGS. STORET is a computerized database in which the EPA and other Federal and state agencies store their water quality data. Well locations and groundwater data are available through WATSTOR and in each state's annual Water Resources Data publication.

State Water Resource Division offices of the USGS are good sources of hydrologic information. Other Federal agencies collecting and analyzing hydrologic data include the Bureau of Reclamation, Tennessee Valley Authority, NWS, Forest Service, and NRCS. Hydrologic information may be available through state, county, and municipal hydrologists. Environmental consulting and engineering firms in the area may provide hydrologic data. Atlases containing regional hydrologic information include USGS (1970), Geraghty et al. (1973), Korzoun et al. (1977), and Miller (1990).

The Water Control section of the Hydrology and Hydraulics division in each United States Army Corps of Engineers district is responsible for collecting and compiling hydrologic data. The Water Control section should be contacted, and relevant hydrologic data should be collected at least once a

month. It is of note that Water Control sections do not necessarily keep data older than a few years, and therefore the USGS should be contacted for historic hydrologic data. It is not uncommon, however, for a district's hydrology and hydraulics division to have already obtained and compiled historic hydrologic data, and therefore they should be consulted to avoid duplication.

Regional water budget

A **regional water budget** is the quantitative evaluation, over time, of the various ways precipitation is dispersed, utilized, stored, or changed in a landscape (Mather 1978). The principal factors in a regional water budget are precipitation, ET, and surface storage. Although precipitation is a true climatic factor, ET is only partially climatically controlled, because ET is also influenced by land cover, land use, soil, geology and topography. As discussed, if ET exceeds precipitation for a period, water is removed from soil storage and conditions arise in which actual ET is less than potential ET. However, if precipitation exceeds ET for a period, water is added to the soil until field capacity conditions are reached. At field capacity conditions, actual ET equals potential ET, and if precipitation continues to exceed ET, overland runoff and aquifer recharge occur. Mather (1978) provides methods for evaluating regional water budgets (Figure 28). Regional water budgets, used in conjunction with hydroclimatologic and synoptic climatologic information (section entitled Synoptic climatology), can provide insight into the large-scale hydrologic response of landscapes to variations in climate.

For large parts of the conterminous United States, precipitation exceeds ET for a significant portion of the year so that surficial and subsurface hydrologic components are added to the local water budget. A **local water budget** represents a systematic accounting of the input, output, and storage of water at a location (Figure 3), and can be expressed in terms of the water budget equation

$$\Delta V = P_n + S_i + G_i - ET - S_o - G_o \pm T$$

where

ΔV = change in volume of water storage

P_n = net precipitation

S_i = surface inflow volume

G_i = groundwater inflow volume

ET = evapotranspiration

S_o = surface outflow volume

G_o = groundwater outflow volume

T = tidal inflow (+) and outflow (-) volume

Evaluation of a wetland water budget generally lacks precision because of the difficulties in accurately measuring the various lithospheric, hydrospheric, and biospheric components that control the flow of water through the landscape. Moreover, the variable nature of weather makes evaluation difficult. Water budget calculations do however provide a basic understanding of the flow of material and energy into and out of wetlands and through landscapes. Water budgets serve as baselines for assessing equilibrium states and predicting environmental impacts. Because timing, duration, and depth of inundation control the capacity of a wetland to provide particular functions, it is essential to consider seasonal and annual fluctuations of all components of the water budget.

Methods for measuring precipitation and ET are discussed in the section entitled Atmospheric components. Methods for measuring groundwater, stream, and overland flow are discussed in the following section.

Hydrologic components of water budgets

Groundwater. Even though groundwater may contribute a small proportion of the total water budget, mixed with other water sources, it can have a significant influence on a wetland nutrient budget. For example, the mixing of as little as 10 percent groundwater from calcareous till with bog waters is sufficient to raise pH from 3.6 to 6.8 (Siegel 1983). Glaser, Janssens, and Siegel (1990) and Romanowicz, Siegel, and Glaser (1993) have shown that groundwater flow can even affect raised bogs. Moreover, groundwater may be available during critical droughts (Romanowicz, Siegel, and Glaser 1993).

Groundwater flow systems are controlled by the composition and geometry of their aquifers. **Aquifers** are subsurface soil, sediment, and rock units which store and convey significant quantities of groundwater (generally thought of as capable of supplying water to public and private wells). Aquifers may be confined, unconfined, or perched. Aquifers which are relatively close to the land surface and are overlain by permeable material extending from the aquifer to the land surface are termed a water table or **unconfined aquifers**. Aquifers which are overlain by an impermeable confining layer are termed artesian or **confined aquifers**. If a well penetrates the confined aquifer, water in the well may rise above the confining layer, and, if hydraulic head is sufficient, water may rise to the land surface. The **potentiometric surface** for a confined aquifer is the level to which water would rise in a series of wells that penetrate a confined aquifer. In some areas, impermeable layers of limited areal extent occur in generally permeable material. In such cases, water moving downward through unsaturated zones is intercepted by the impermeable layer and accumulates, forming a saturated zone. Such zones are termed a **perched aquifers**. Perched aquifers are common in glacial outwash where muds of former lakes, ponds, and wetlands produce impermeable layers in the subsurface.

Groundwater flow rate and direction are evaluated by measuring **hydraulic head** which is the potential energy of the groundwater system at point of measurement, and is the sum of elevation, pressure, and velocity head (Fetter 1988; Smith and Wheatcraft 1992). Groundwater velocities are generally so low that this kinetic component of head can almost always be ignored. Elevation head is the height of a water table above some datum, commonly sea level, although for convenience a local datum may be preferred. Hydraulic head is generally expressed in terms of values above atmospheric pressure, generally measured in units of length (e.g., mm Mercury). **Hydraulic gradient** is the difference in hydraulic head between two points (Figure 36). Hydraulic gradients occur both vertically and laterally.

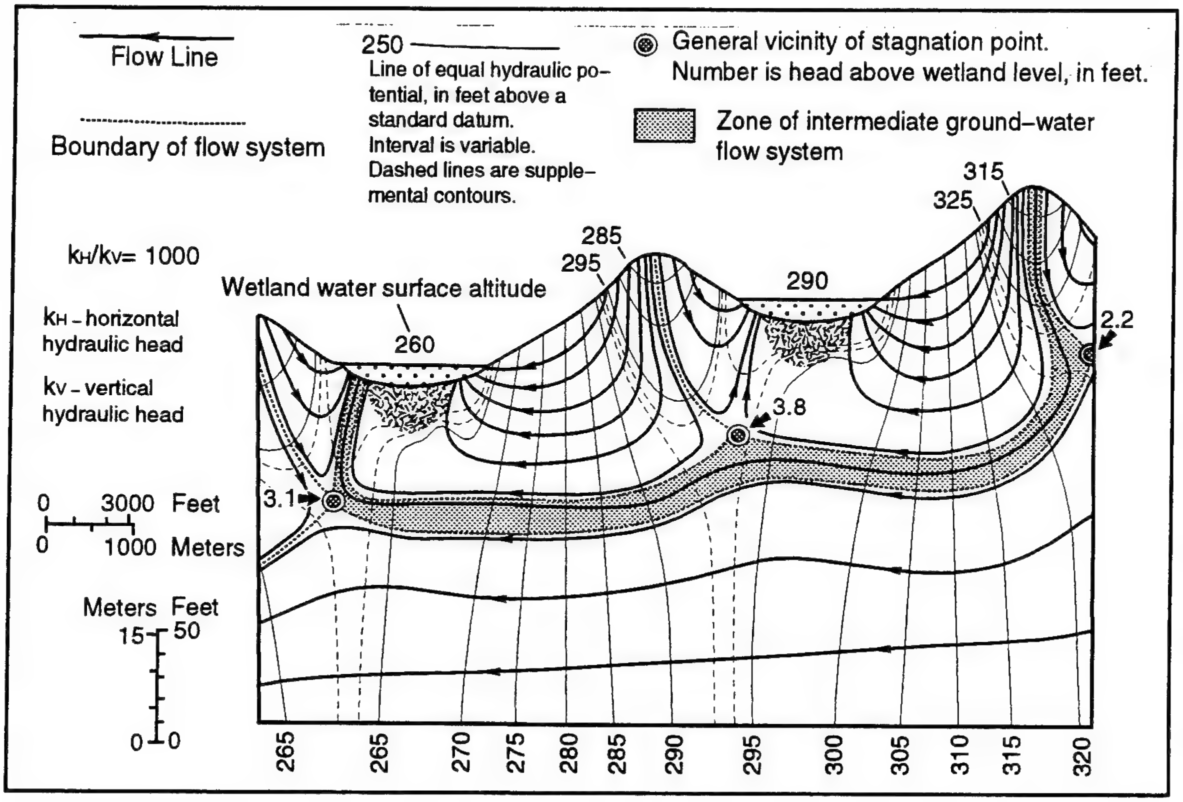


Figure 36. Hydraulic section showing local, intermediate, and regional flow systems. (After Winter (1976))

There are commonly multiple, interacting groundwater flow systems within a landscape. Winter (1976) recognized three major groundwater flow components: local, intermediate, and regional. Local flow systems recharge at topographic highs and discharge at adjacent lows. Intermediate flow systems discharge beyond adjacent areas of low elevation of the water table (Figure 36). Regional flow systems recharge at regional groundwater divides and discharge at major lakes and rivers. Of special interest are the lines, known as divides (Winter 1976) which occur where different groundwater flow systems diverge. The **stagnation point** is the location along the divide at which head is minimum (Figure 36). A value of head exists at the stagnation point and its value relative to the head represented by the adjacent wetland water

level determines the interaction of wetlands and the groundwater system (Winter 1976). Therefore, if stagnation points can be located in the field, a great deal of information about the hydrodynamics of the groundwater flow system around wetlands can readily be obtained. For example, if the head at a stagnation point is higher than an adjacent wetland water level, groundwater tends to discharge into the wetland. Whereas, if the head at a stagnation point is less than the wetland water surface elevation, recharge tends to occur (the volume depends upon the permeability of the wetland substrate). Anderson and Munter (1981) demonstrate that stagnation points may develop seasonally.

Groundwater chemistry is partly controlled by the length of time water is in contact with minerals in an aquifer. Therefore, waters from intermediate and regional systems are likely to contain more, and a wider variety of, dissolved minerals than groundwater from local flow systems. Therefore variations in water chemistries between adjacent waterbodies is not at all surprising. On the contrary, after becoming aware that every waterbody has a unique groundwater contribution, variations in water chemistry are to be expected (Winter 1976).

As mentioned previously, many wetlands in the United States occur on late Pleistocene to Holocene sediments so that wetland groundwater systems tend to be controlled by shallow, local flow systems in unconfined, unconsolidated (Quaternary) aquifers. Such systems tend to be highly dynamic in which fluctuations in flow rates and water table elevations vary seasonally and annually. However, many wetlands have, over time, developed low permeability substrates which tend to isolate them from surrounding groundwater systems. In many others, peat accumulation has created enough relief to isolate or partially isolate these wetlands from adjacent groundwater flow systems.

The groundwater component of the water budget is one of the most difficult components to measure because:

a. Piezometers and observation wells measure only a single point or line in a large-scale 3-D system. Because wells and piezometers are relatively expensive and time consuming to install and monitor, their number is typically inadequate to fully characterize groundwater flow systems.

b. Many mathematical models used to describe groundwater flow, including Darcy's Law, assume homogeneous substrates. Permeabilities in natural subsurface materials, however, vary over nine orders of magnitude (Figure 23), and inhomogeneities in rocks and sediments are the rule rather than the exception.

c. Groundwater flow systems are dynamic both seasonally and annually (Meyboom 1966; Winter 1976) and therefore require frequent monitoring on a long-term basis.

d. Methods of measuring sediment-soil permeabilities, hydraulic head, etc., are not standardized, nor are criteria for selecting the most suitable methods and equipment.

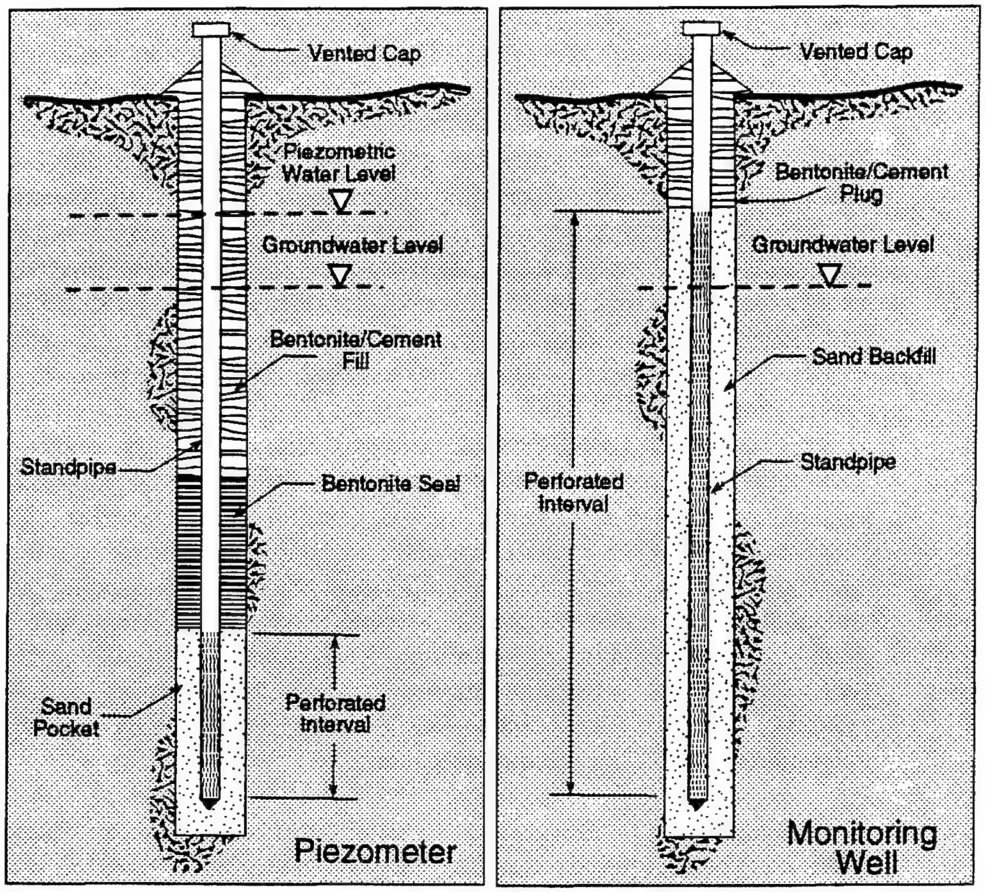
Groundwater flow rate and volume are conventionally determined by measuring the permeability (hydraulic conductivity) of the aquifer, measuring the hydraulic head, and then calculating flow rate per unit cross-sectional area using the empirical formula - Darcy's Law. There are, however, other methods with which to characterize groundwater flow systems and their interaction with wetlands. Both conventional methods using Darcy's Law and other more qualitative methods of characterizing groundwater flow are briefly discussed below.

Realistic assessment of shallow groundwater flow requires a large number of piezometer nests (Hollands 1987). **Piezometers**, specifically designed to measure the hydraulic head, or piezometric water level, in a zone small enough to be considered a point, are used to measure hydraulic head at depth (Figure 37). In contrast, **monitoring wells** measure the average head, or water table level, for an interval (Figure 37). Sprecher (1993) described proper installation of piezometers and monitoring wells in wetland settings. Vertical hydraulic gradients are generally measured by piezometer nests which are a group of piezometers at the same location, extended, and sealed at various depths. Lateral gradients are measured by piezometers open at the same level in the aquifer at different locations. **Hydraulic gradients**, or the rate of change in hydraulic head per unit distance, indicate direction of groundwater movement in which flow is from higher to lower head. In unconfined aquifers, lateral hydraulic head is commonly measured as the difference in water table elevation between observation wells.

In unconfined aquifers, the water table commonly follows the topography and hence groundwater tends to flow from topographic highs to lows. Determination of the direction of groundwater flow, however, requires at least three wells open at the same level in the aquifer (Heath 1983). The overall, 3-D picture of the groundwater flow system requires properly constructed flow nets (Heath 1983; Cedergren 1989). **Flow nets** are composed of equipotential lines and flow lines (Figure 36). **Equipotential lines** connect points of equal hydraulic head. **Flow lines** are the idealized flow path of groundwater as it moves through the aquifer. Flow lines cross equipotential lines at right angles in properly constructed flow nets. Cedergren (1989) provides a more thorough review of flow nets and flow net construction.

Groundwater flow takes place in a saturated, porous medium, and is described by an empirical equation known as **Darcy's Law**. This law states that the rate of groundwater flow is proportional to (a) the hydraulic gradient and (b) the hydraulic conductivity or permeability of the soil, sediment, or rock. It appears to apply adequately to most mineral soils, and standard techniques can be used to determine hydraulic head, hydraulic conductivity, and specific yield. Darcy's Law can be written as

$$Q = k \cdot i \cdot A$$



a. Piezometers are used to measure piezometric water level (hydraulic head) at a particular depth

b. Monitoring wells are used to measure water table levels.

Figure 37. Schematic diagram of a piezometer and a monitoring well

where

Q = rate of seepage in a cross section with an area

A = area normal to the direction of flow, under a

i = hydraulic gradient

k = coefficient of permeability, or hydraulic conductivity

The coefficient k is equal to the discharge velocity under a hydraulic gradient of 100 percent and is measured as velocity (Cedergren 1989). Determining the hydraulic conductivity of an aquifer is the most challenging aspect of solving Darcy's equation. The general relationship between the coefficient of permeability and rock-sediment type is shown in Figure 23.

Although there are laboratory methods for measuring the hydraulic conductivity of subsurface samples, they only represent minute volumes of earth material at a limited number of points within a large mass. Therefore field methods that evaluate responses to induced changes in water levels in wells are generally used to determine hydraulic conductivity. Two general categories of well tests are used to determine subsurface permeability: (a) those that evaluate the response (i.e., change and rate of change in water levels) of well pumping by monitoring surrounding observation wells, and (b) those that evaluate water level response of the pumped well itself. A wide variety of techniques and formulae are available for pumping tests using surrounding observation wells (Brackensiek, Osborn, and Rawls 1979; Fetter 1988; Cedergren 1989). Because pumping tests using observation wells is expensive, the discussion here is therefore limited to pumping tests in a single hole.

Hvorslev (1951) noted that whenever a shallow observation well or piezometer was installed, the initial hydrostatic pressure in the well seldom equaled surrounding pore water pressure, and that water must first flow to or from the hole to reach equilibrium with surrounding sediments or soils. He also noted that the rate at which equilibrium was attained depended upon the composition and texture of the soil surrounding the well. From these observations, various techniques have been devised to measure hydraulic conductivities in soils by measuring the rate of water level change in a borehole after pumping. Two of these borehole testing techniques are briefly reviewed here: the auger-hole and the piezometer method.

The **auger-hole method** is the procedure most widely used to measure hydraulic conductivity of saturated soils (Amoozegar and Warrick 1986). A hole is drilled using a standard bucket auger to at least 30 cm below the water table. The depth of the hole (H), diameter of the hole (2r), and distance between bottom of the hole and underlying impermeable layer are determined (Figure 38). Water is then pumped from the hole and the rate of the rise of the water is measured. Hydraulic conductivity (k) can then be calculated using the equation

$$k = \{4.63\ r^2/[y(H + 20r)(2 - y/H)]\}(\Delta y/\Delta t)$$

where

r = radius of hole

H = depth to water table

y = difference between the depth of the groundwater table and water in the hole

$\Delta y/\Delta t$ = the change in water level in the hole (y) with respect to time (t)

The value k can also be estimated using the nomograph in Amoozegar and Warrick (1986; their Figure 29-3).

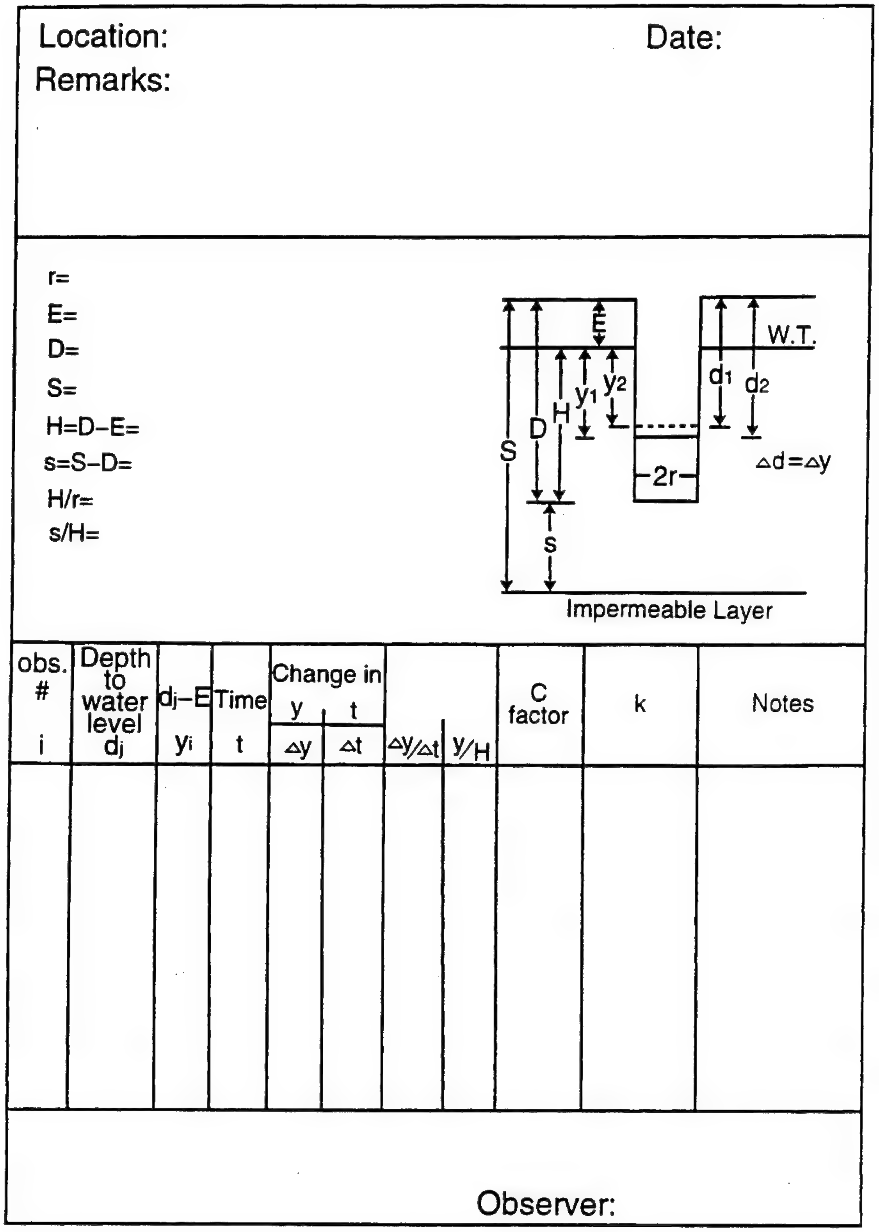


Figure 38. **Data sheet for calculating hydraulic conductivity (k) using the auger-hole method. The C factor, which is a function of the shape to the bottom of the hole, can be determined from Amoozegar and Warrick (1986), their Table 29-1**

The cased-hole or **piezometer method** is another widely used procedure to measure hydraulic conductivity (Amoozegar and Warrick 1986). The depth of the cased-hole (H), its diameter (2r) and distance between bottom of the hole and underlying impermeable layer (s) are determined (Figure 39). Water is then removed, the rate of rise of water measured, and the hydraulic conductivity (k) is calculated using the equation

$$k = \{\pi r^2/[C(t_{i+1} - t_i)]\} \ln(y_i/y_{i+1})$$

where

r = radius of the basal cavity

y_i = the difference between the depth of groundwater and the depth of water in the pipe at time t_i

y_{i+1} = the difference between the depth of groundwater and the depth of the water in pipe at time t_{i+1}

C = a shape factor (see Amoozegar and Warrick 1986, Table 29-2)

Location: Date:

Remarks:

$r=$

$E=$

$D=$

$S=$

$h_c=$

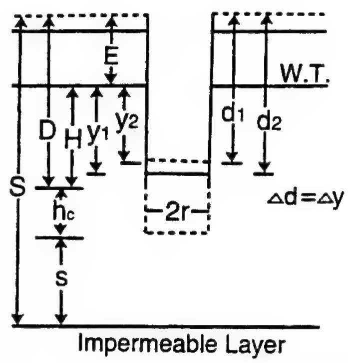
$H=D-E=$

$s=S-D-h_c=$

$h_c/r=$

$H/r=$

$s/r=$



obs. # i	Depth to water level d_i	d_i–E y_i	Time t	Ratio y_i/y_{i+1}	Change in time Δt	C/r factor	k	Notes

Observer:

Figure 39. Data sheet for calculating hydraulic conductivity (k) using the piezometer method. The factor, which is a function of the shape of the bottom of the hole, can be determined from Amoozegar and Warrick (1986), their Table 29-1

The shape factor is concerned with the size and dimensions of the porous zone around the perforated interval at the base of the piezometer (Figure 37a). Hydraulic conductivity, *k*, can also be estimated using the nomograph of Amoozegar and Warrick (1986; their Figure 29-7). Hvorslev (1951), Reeve (1986), and Cedergren (1989) also describe the piezometer method for evaluating soil permeability.

Once sediment/soil hydraulic conductivities are known, Darcy's Law can then be used to calculate flow rates:

$$Q = V \cdot A$$

where

Q = volume of water per unit time

V = volume of water moving through cross-sectional area A

Other, less quantitative methods to evaluate groundwater flow include: (a) ratio of shoreline length to wetland area, (b) vegetation, (c) wetland water chemistry, (d) water temperature, (e) seepage meters, and (f) comparison of wetland water versus groundwater level fluctuations over time. Each of these methods is briefly described below.

Numerous studies have demonstrated that seepage to and from lakes and wetlands decreases exponentially from the shoreline to lake/wetland center (Millar 1971; McBride and Pfannkuch 1975; Lee 1977; Winter 1981). Millar (1971) determined that water loss from depressional wetlands (potholes) varied directly with length of shoreline per unit area, and therefore, inversely with size of wetland. Measuring the ratio of wetland shoreline length to wetland area only works in wetlands with standing bodies of water, and then the measurement only provides qualitative estimates and does not determine whether seepage is flowing into or out of a wetland. It does, however, provide insight into the relative importance of seepage in wetlands and is an initial step toward designing a more detailed groundwater monitoring program.

Vegetation is sensitive to water depths and chemistries, and therefore is an excellent indicator of hydrologic conditions. There are commonly notable differences in vegetation between perched wetlands and those situated in unconfined aquifers (Bay 1967). Glaser, Janssens, and Siegel (1990) used changes in vegetation in core samples to evaluate changes in wetland groundwater flow over time. Mitsch and Gosselink (1993) and Theriot (1993) have reviewed the use of vegetation as indicators of wetland hydrology.

Water chemistry in wetlands with significant groundwater discharge is similar to surrounding groundwater chemistry. In addition, depressional wetlands and lakes without surface outlets and little groundwater recharge tend to be saline because water is removed only by ET which leaves behind, and eventually concentrates, soluble material. This phenomenon is not restricted

to warm climates; increased salinities in isolated wetlands and lakes have been documented in the northernmost states and Canada (Różkowska and Różkowski 1969).

During the growing season, groundwater temperatures are significantly less than shallow surface water temperatures in wetlands. Hence, a series of temperature measurements in wetlands can be used to locate areas of groundwater discharge by locating areas with anomalously low temperatures. On the other hand, Bay (1967) noted that portions of wetland water surfaces with connections to the groundwater flow system remained unfrozen even though air temperatures reached as low as -37°C (-35°F). Although qualitative, this method may serve as an initial step toward locating areas of discharge which could then be quantified using seepage meters and piezometers.

Devices have been designed to directly measure flow of water into and out of wetland and lake bottoms. A commonly used seepage meter is made from the end of a 208 liter (55 gal) drum cut to a height of 15 cm (6 in.) and fit with a stopcock and a plastic bag on its top (Lee 1977; John and Lock 1977). The open end of the drum is pushed down into the wetland bottom until the top of the drum, with stopcock open and bag removed, is 1 to 2 cm (0.4 to 0.8 in.) above the wetland bottom. The portion of the meter where the stopcock is positioned should be slightly higher to facilitate removal of air. After air and organisms escape through the open stopcock, the bag which contains a known volume of water is attached to the stopcock which is then opened. Volume change in the bag, for a given length of time, is measured to determine the rate at which water seeps into or out of the wetland bottom. Lee (1977) and Lee and Cherry (1978) provide further discussions on seepage meters and their operation. Burke, Hemond, and Stolzenbach (1980) and Hemond and Burke (1981) described a seepage meter designed for tidal marshes. Although seepage meters are potentially very useful, they only represent a point sample both in time and space (Winter 1981). In addition, seepage meters are most accurate in sandy bottoms, but may experience anomalously high flow through material disturbed along the cutting edge of the barrel in clayey or organic sediments. Groundwater flow may vary seasonally so that measurements of groundwater flow using seepage meters requires measurements at various times of the year.

Wetlands with relatively constant water levels are likely to be well connected to the groundwater system. By monitoring wetland water levels and comparing them to surrounding water table levels it is possible to determine that (a) the wetland is well connected to the groundwater system if wetland and water table level fluctuations coincide, (b) groundwater discharge is likely if surrounding water table levels are higher than wetland water levels, (c) groundwater recharge is likely if wetland water levels are higher than surrounding water table levels, and (d) a combination of groundwater discharge and recharge are likely if the water table is consistently higher on one side of the wetland. Elevations of the water table relative to the wetland are likely to change season to season and year to year. Therefore water table and wetland water levels should be routinely measured, and changes in their relative heights should be monitored over time.

Surface water. Two principal forms of surface flow can be distinguished: streamflow and overland flow. Analysis of surface water flow begins by defining the wetland watershed. Obviously the relative effect of direct surface runoff on a prairie pothole and a tidal marsh located in the lower reaches of a major river system are quite different. It follows then that the size of the watershed dictates the relative importance of direct overland flow. No matter how large the watershed, the entire catchment should be taken into consideration, with commensurate degree of detail. The wetland watershed should be outlined on topographic maps and its area calculated. Because many wetlands are located in areas of low relief, definition of the wetland watershed from topographic maps with 5- to 20-ft contours may be difficult and require field analysis. Two components of the watershed should be distinguished: that portion in which overland flow enters streams and that portion in which overland flow directly enters the wetland. The position of the wetland in the watershed and the influence its location has on the flow of water and sediment through the wetland should be evaluated.

Two components of streamflow are generally recognized: baseflow and quickflow. **Baseflow** is the steadystate flow of a stream under normal conditions in which water is supplied by its tributaries and groundwater discharge. **Quickflow** is enhanced discharge of a stream associated with surface and near-surface runoff resulting from a precipitation event.

Streamflow measurement generally involves recording water levels or stage above datum, measuring streamflow rates at different stage levels to establish the relationship between water level and discharge (generating a rating curve), and using the rating curve to transform the stage information into a discharge record (Mosley and McKerchar 1992). Stage measurements are usually made at gaging stations. Stream gage stations typically consist of a float in a stilling well that is connected to the stream by intake pipes. Pressure transducers or manometers may be used instead of a float to detect stage level.

Where permanent stage gages are not present, it is possible to measure stream stages using a hand-held triangular staff. The triangle should be elongated to make it streamlined. The apex of the triangle should point up current during measurement. Periodic measurement should be taken at the same locations which preferably are along straight reaches of the stream and on firm substrates. To avoid interference, the staff should be held as far away as possible from the person taking the measurement.

Streamflow rates are usually measured by current meters, which contain a rotating element whose speed of rotation is proportional to the water velocity (Vanoni 1975; USGS 1977). Stream discharge is measured at several points along a stream transect and at a series of depths at each point. Using the channel cross-sectional area (A), streamflow (V) measurements are integrated to determine the discharge (Q). Streamflow rates are evaluated a number of times, at different stage levels, to establish the relationship between stage and discharge, thereby generating a rating curve (Figure 40).

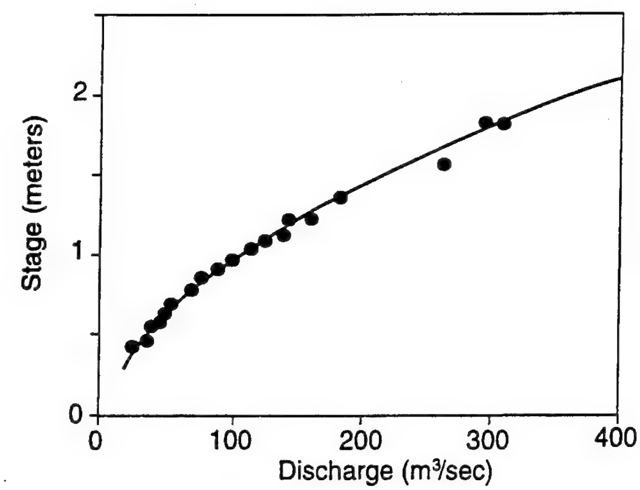


Figure 40. A discharge rating curve which establishes the relationship between stage and discharge so that discharge can be determined from stage measurement, thereby avoiding costly and time-consuming manual discharge measurements

Rating curves eliminate the necessity to manually measure streamflow to determine discharge rates in channels. Flow at gaging stations in natural channels, however, must be periodically remeasured because changes in channel geometry (from scour or deposition) alter the relationship between stream stage and discharge. Artificial flow control structures such as weirs and flumes have relatively fixed stage/discharge ratios and thus need less frequent manual streamflow measurements. Further descriptions of stream gaging and streamflow measurement methods are available in Carter and Davidian (1968), Vanoni (1975), USGS (1977), Gwinn et al. (1979), and Rantz et al. (1982a,b).

A record of open channel discharge as it varies with time is known as a hydrograph (Figure 13). Hydrographs can measure individual storm events (Figure 13) or annual streamflow variation (Figure 13). Both time scales are useful for monitoring wetlands. The shape of a storm hydrograph is controlled not only by the intensity and duration of the precipitation event, but also by the size, surface characteristics, and morphometry of the watershed (section entitled Watershed morphometry). Smaller watersheds tend to have spikey hydrograph signatures because intense rainfalls are localized and they lack temporary floodflow storage areas. Large watersheds tend to have smoother hydrograph signatures because of spatial heterogeneity of their water sources and they have broad expanses to absorb and gradually release waters. Overland flow and baseflow are conventionally differentiated on a storm hydrograph by extending a line from the foot of the rising limb of the curve to the foot of the falling limb (Figure 13).

Annual discharge hydrographs (Figure 13), which show variations in discharge over the course of a year, are an effective means to monitor baseflow

over time, analyze seasonal and annual streamflow variations, and compare with wetland function performance. A more detailed discussion of hydrographs can be found in Principles of Hydrology by Ward (1975).

For ungaged wetland watersheds, two methods for evaluating stream discharge are: (a) stream gage data from a nearby watershed in which topography, land cover, and soils are similar to the watershed being evaluated, or (b) the Manning equation. Because land features and weather conditions commonly vary over short distances, gage data from other watersheds should be used with caution and in conjunction with the Manning equation. The **Manning equation** considers the channel roughness, n, the hydraulic radius, R which is the cross-sectional area (m^2) divided by the wetted perimeter (m), and channel slope, s:

$$Q = R^{2/3} s^{1/2} / n$$

Examples of roughness coefficients are given in Table 19. The Manning equation is particularly useful for estimating streamflows where velocities are too low to measure directly and to estimate flood peak flows from high water marks. More detailed discussions of the Manning equation are presented by USGS (1989) and Mosley and McKerchar (1992).

Table 19
Roughness Coefficients for Manning Equation Used to Determine Stream Flow in Artificial Canals and Natural Channels

Stream Conditions	Manning Coefficient, n
Straightened earth canals	0.020
Winding natural streams with some plant growth	0.350
Mountain streams with rocky streambed	0.040-0.050
Winding natural streams with high plant growth	0.042-0.052
Sluggish streams with high plant growth	0.065
Very sluggish streams with high plant growth	0.112

After Mitsch and Gosselink (1993).

During a typical rainfall episode, water at the Earth's surface initially infiltrates into the soil. As rainfall continues, the rate of infiltration is reduced as soil pores become filled, and, if the rain continues, the point is reached at which the rainfall rate exceeds infiltration rate, the soil becomes saturated, and overland flow occurs. It is not then surprising that the amount of precipitation is the principal factor controlling runoff volumes. Other factors controlling runoff include geology, basin morphometry, soil composition and texture,

vegetation, land use, and meteorologic factors that control the nature of rainfall intensity and duration (Patton 1988).

The amount of overland flow is highly dependent on soil infiltration rates. As discussed previously, infiltration rates are dependent on soil type, land use, and land cover. Antecedent runoff conditions (ARC) also affect infiltration rates. Rainfalls 5 to 30 days prior to a rainfall event are commonly used to estimate watershed wetness. The SCS (1985) recognizes three levels of ARC's: I - lowest runoff potential, II - average conditions, and III - highest runoff potential (Table 12; Figure 41).

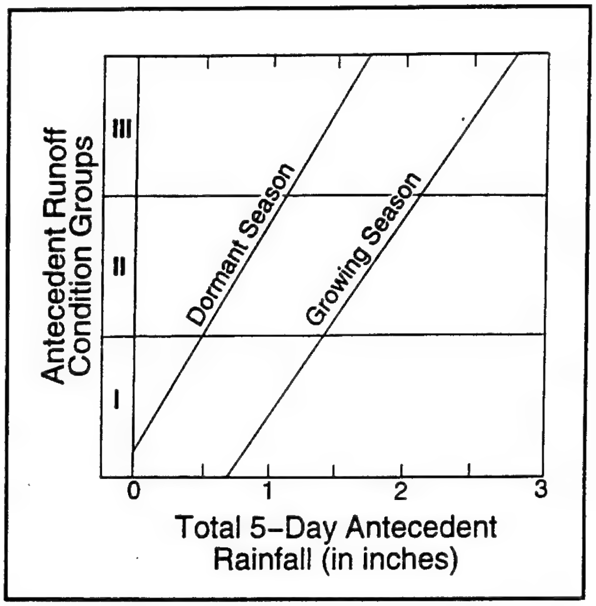


Figure 41. Graph for estimating antecedent soil moisture conditions. After SCS (1985)

Two types of runoff are generally recognized: surface runoff and interflow. **Surface runoff** occurs when soil is at field capacity or rainfall rate is greater than infiltration rate. Surface runoff typically occurs as sheetflow and appears on the hydrograph after initial demands of interception, infiltration, and surface storage have been satisfied. Surface runoff varies during a storm event and typically ends soon after. In arid and semiarid regions, surface runoff is commonly reduced or lost to infiltration. The second type of runoff, **interflow**, occurs where infiltrated rainwater encounters an underground zone of low transmission, travels above the zone to the soil surface downslope. Interflow is commonly referred to as quick return flow because it appears in the hydrograph during or soon after the storm event. Although interflow is not true surface flow, it is restricted to the upper soil profile, travels parallel to the landsurface, does not mix with the groundwater system, and quickly reappears at the surface. It is therefore a common practice to consider it as overland flow.

Determination of overland flow volumes in gaged watersheds is fairly straightforward. For example, data in Table 20 are hypothetical mean daily flows for February 27 to March 10. Note that low flows occur on March 2 and again on March 9; these 2 days mark the beginning and end of a rain event. Total discharge during the flood period was (54 + 94 + 72 + 56 + 48 + 31 + 18 m^3/sec) • (60 sec/min • 60 min/ARC • 24 ARC/day) = 322,227,200 m^3 (1,137,942,000 ft^3). Average base flow for the March 3 to 9 period is (16 + 18)/2 = 17 m^3/sec (607 ft^3/sec). The base flow volume for the 7-day flood period (starred discharges) is 7 day • 17 m^3/sec • 60 sec/min • 60 min/ARC • 24 ARCs/day = 10,281,600 m^3 (~363,051,000 ft^3).

Table 20
Mean Daily Discharge During Flood Period

Date	Discharge (m^3/s)	Remarks
Feb. 27	27	Flow from previous rise
28	24	Same
Mar. 1	19	Same
2	16	Low point of flow (baseflow)
3	*54	Rise of annual flood begins
4	*94	Peak rate
5	*72	Flood receding
6	*56	Same
7	*48	Same
8	*31	Same
9	*18	End of flood period
10	27	New rise begins

Runoff during the 7-day period then was 32,227,200 m^3 - 10,281,600 m^3 = 21,945,600 m^3 (~774,899,000 ft^3). For a watershed of 256 km^2 (98 $miles^2$), the average depth of direct runoff is 21,945,600 m^3/(256km^2 • 1,000,000 m^2/km^2) = 0.086 m or 8.6 cm (3.4 in.). If the average rainfall depth for the 7-day period was 21 cm (8.4 in.), then ~40 percent of the rainfall was converted to runoff. The remainder of the rainfall was intercepted by plants, returned to the atmosphere via ET, is stored in surface storage areas above the gaging station, is temporarily stored as soil moisture, or infiltrated into the groundwater system.

Storm runoff volumes in gaged watersheds can be evaluated using storm hydrographs. For example, in Figure 13 the average baseflow (average input from groundwater) is 244 m^3/sec. The portion above the baseflow line represents overland flow, and its volume is equal to the area under the graph. According to Figure 13, quickflow occurred over a 4.2 day or 37,584 sec period. Overland flow volume can be approximated by summing the areas of a series of rectangles which approximate the area under the graph. In Figure 13, 14 rectangles are used in which each represent 37,584/14 = 2,685 sec. Overland flow volume can be calculated by multiplying the height of each rectangle by the time duration it represents, and summing. In the case of Figure 13, the volume of overland flow is ~11.1 • 10^6 m^3. In a 593-km^3 watershed that experiences 3.7-cm rain, the total rain volume = 21.9 • 10^6 m^3 such that approximately 50 percent of the rainfall reached the stream via overland flow. The other 50 percent was intercepted by plants, returned to the atmosphere by ET, remained as soil moisture, or percolated downward to the water table. In some cases, the total water volume (baseflow + overland flow) that flowed during a rainfall is sought. In such a case, the rectangles are extended to the abscissa. In Figure 13, the total streamflow volume for the 4.2-day rainfall event is ~14.7 • 10^6 m^3.

If all or portions of the watershed are not gaged, runoff can also be calculated by applying one of the many available rainfall/runoff models. These numerical models range from simple, one-dimensional versions to sophisticated models that take into account a multitude of landscape parameters and require hundreds of man-hours at this time to prepare and run (Ward 1975; EPA 1992). Presented below is a simple procedure for estimating runoff from rainfalls of brief duration (USGS 1977; Mather 1978; Gwinn et al. 1979; Simon, Stoerzer, and Watson 1987). The SCS (1985), who devised this method, provide a more detailed description.

To calculate runoff in an ungaged watershed from a particular rainfall event:

a. Determine the surface drainage area of the watershed.

b. Determine the various land uses of the watershed (Table 12).

c. Calculate the portion of the watershed for each land use class (Table 12).

d. Determine the Hydrologic Soil Group for each soil type from soil survey maps and the SCS (1985). Hydrologic Soil Groups are briefly discussed in the section entitled soils.

e. Determine the CN for each land use type taking into account the ARC (Figure 41; Table 12).

f. Calculate the composite curve number by multiplying the CN times the portion of watershed covered by that land use, and adding (Table 12).

g. Determine average depth of the rainfall event in the watershed (section entitled Precipitation).

h. Using the average rainfall depth and the composite CN, estimate runoff using Table 12 and Figure 42.

For example, suppose that an average of 9.6 cm (3.8 in.) of rain fell over a forested (good cover) watershed in which soils are in the Hydrologic Soil Group C, and ARC = II. To determine direct runoff, the CN must first be ascertained. In Table 12, a CN = 70 is read for forest with good cover, Hydrologic Soil Group C, and ARC = II. To estimate runoff, enter Figure 42 at rainfall of 9.6 cm (3.8 in.) and CN = 70, and runoff = 3.8 cm (1.5 in.). If the watershed is 14 km^2, that would be 532,000 m^3 of runoff.

Differing ARC results in variations in the quantity of overland flow. For example, for a residential area (38 percent nonporous area) with Hydrologic Soil Group B and ARC = II, CN = 75 (Table 12). From Figure 42, a 10.4-cm (4.1-in.) rain yields direct runoff = 4.3 cm (1.7 in.). At other times, the same residential area may have ARC = I so that CN = 88 or ARC = III so that CN = 88 (Table 12). Under these conditions, a 10.4-cm

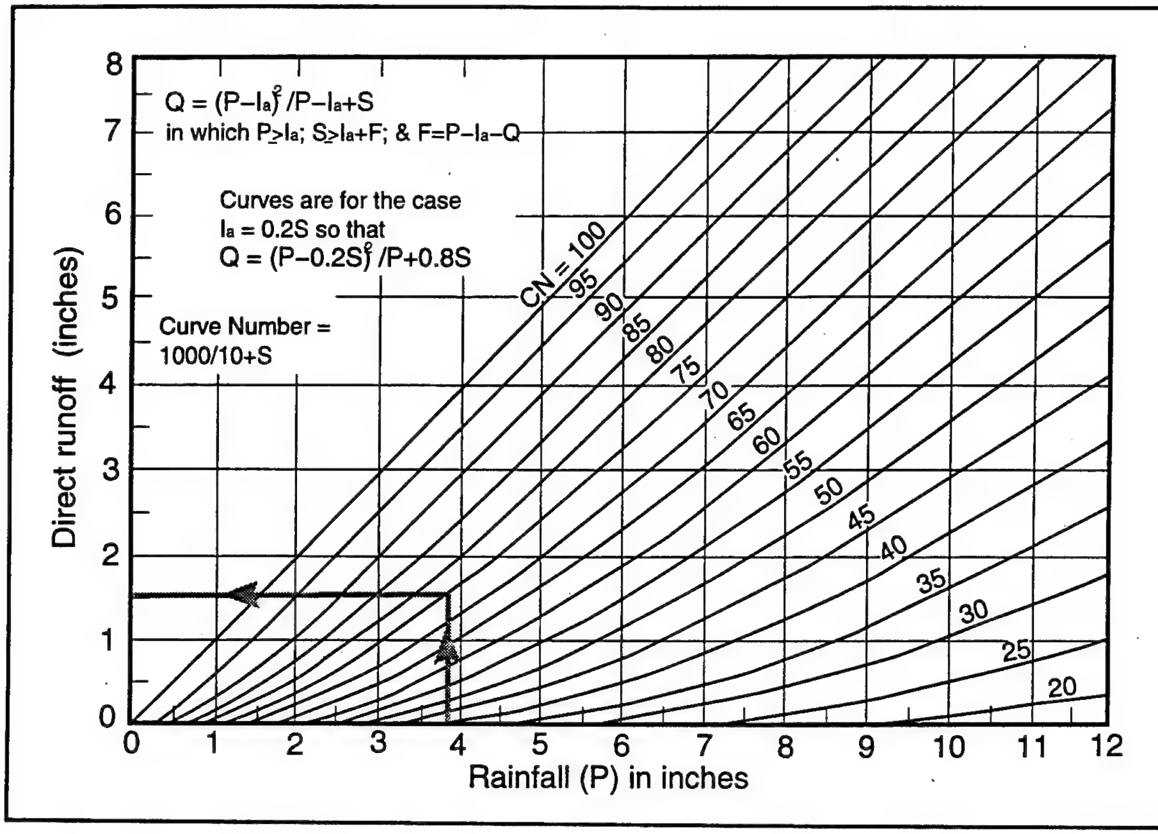


Figure 42. Relationship between rainfall totals and direct runoff for various curve numbers. The example shown by the gray line is described in the text. Parameters and formulae in the upper left of graph are discussed in SCS (1985). (After SCS (1972) and Mather (1978))

(4.1-in.) rainfall would produce runoffs of 1.8 cm (0.7 in.) and 9.6 cm (2.9 in.), respectively (Figure 42).

Watersheds typically have a variety of soil types and land uses (CN's). Suppose a watershed of 12 km^2 has 6 km^2 of residential area (38 percent impervious), 2 km^2 park, and 4 km^2 commercial. All soils are in the Hydrologic Soil Group B and ARC = II. Table 12 shows that CN = 72 for residential, CN = 61 for a park, and 92 for commercial areas with the stated soil and moisture conditions. The composite CN for the watershed is $[72 \cdot (6/12)] + [61 \cdot (2/12)] + [93 \cdot (4/12)] = 77$.

The hydrologic effects of changes in land use and land cover can be predicted using this method. Say for example a 7.8-km^2 watershed with Hydrologic Soils Group B and ARC = II is currently composed of 4.1 km^2 of forest in good condition (CN = 55), and 3.7 km^2 pasture in good condition (CN = 61). There is a plan to develop 1.1 km^2 into a residential area (30 percent impervious) in which CN would be 74 under the given soil and moisture conditions. The remaining watershed would be composed of 3.8 km^2 forest and 2.1 km^2 pasture. At present, the composite CN = $[(55 \cdot 4.1/7.7) + (61 \cdot 3.7/7.7)] = 58$ After construction of the residential area, the composite CN would be $[(55 \cdot 3.8/7.7) + (61 \cdot 2.9/7.7) + (72 \cdot 1.1/7.7)] = 60$.

Using Figure 42, a 10.4 cm (4.1 in.) rainfall at ARC = II would produce 0.7 in. of runoff before and 0.8 in. after development. For the 7.8 km^2 watershed, runoff volume would increase from 54,600 m^3 to 62,400 m^3, an additional 7,800 m^3 or 14 percent runoff from this modification of the watershed. It should be kept in mind that such modifications induce a series of changes including greater peak flow rates (higher and sharper storm hydrographs) and increased sediment, nutrient, and toxicant yields during storm events. Increased runoff also leads to a proportional decrease in groundwater recharge.

Water quality modification by wetlands is related to several features including water and nutrient residence time, sedimentation rates, water level, cation exchange capacity of organic material, and uptake and assimilation by biota. In the past, water management practices tended to stabilize water levels. If water level fluctuations in wetlands continue to occur, they are likely maintained within certain limits. Water level fluctuations characteristic of natural wetlands commonly at odds with water level control desired in many areas. To find a water level schedule that is amenable to enhancement of desired wetland functions and to other societal needs, determine the degree of water control in the area, when it was emplaced, and assess impacts on wetlands. In addition, determine the height and timing of water level fluctuations that would maximize wetland functions. Then work out an integrated plan that takes into account current water level practices and those which will most benefit wetlands. Figure 43, which is based upon 28 years of record from the Big Cypress Swamp, Florida, presents a simple method for analyzing wetland water levels over time. The graph shows that most water-level fluctuations take place during the dry season which implies that rain is more variable in the dry and in the wet season.

Hydroperiod is the timing and duration of flooding or saturated soil conditions in a wetland. Hydroperiods control plant community composition by eliminating species intolerant of extended inundation, influencing timing of establishment of seedlings, and influencing the frequency of fire. As latitude and elevation increase, the frequency and duration of frozen conditions also increase, such that the length of growing seasons decrease. Hence, wetlands in the northern United States commonly have hydroperiods of less than 3 months, whereas wetlands with peats in Florida require inundation periods of at least 8 months to ensure rates of peat accumulation at least equal to rates of decomposition (Deuver 1988).

Wetland water volume estimates are used to compare the quantity of water passing through a wetland system to the hydrologic cycle of the surrounding landscape. Moreover, wetland water volume estimates are used to calculate the residence times of water in wetlands. Of course, wetland water volume varies seasonally and annually, and records of these changes are necessary for effective wetland management. Methods of estimating wetland water volume include:

a. Planimeter the extent of inundation, determine average water depth and calculate volume (area times depth).

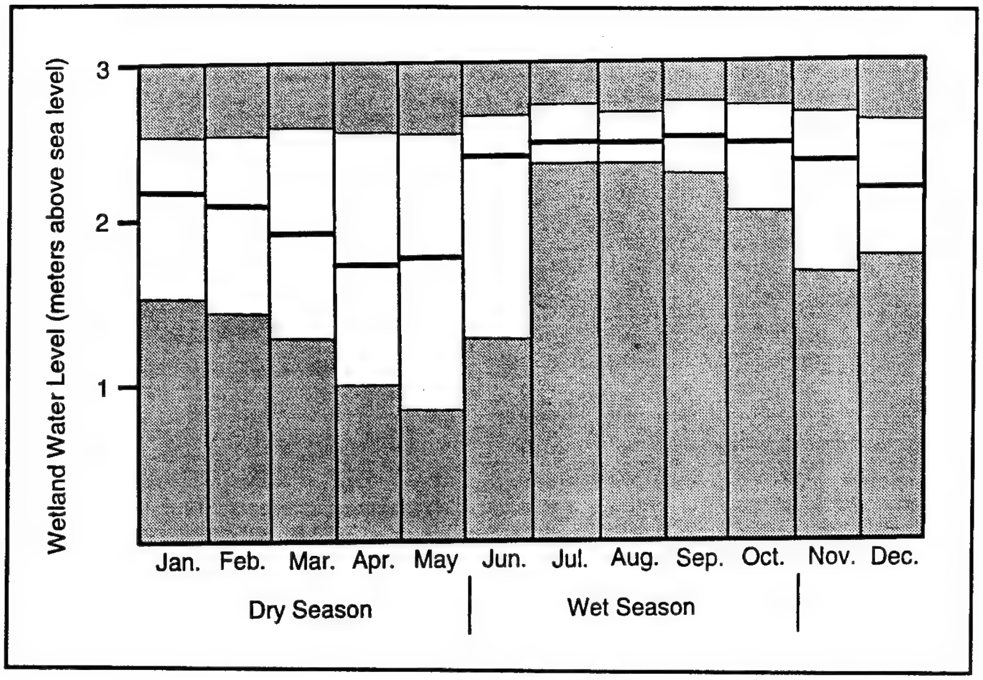


Figure 43. Mean monthly (heavy line) and absolute maxima and minima (white box) water levels at a wetland site. After Deuver (1988)

b. Take a series of depth profiles, subdivide wetland into numerous sectors of equal depth, calculate areas of each sector, add together areas of equal depth, multiply the summed areas of equal depth times their depth, and add these volumes.

Method 2 is recommended whenever possible. Wetland water volumes should be measured on a seasonal basis. Records should be kept and graphed on standard computer software such as Quattro® Pro. Water volume data are especially useful when plotted in relation to some other parameter or parameters such as vegetation cover or bird population to determine water volumes that maximize desired wetland functions.

Residence time and its reciprocal **turnover rate** provide information about the length of time that water remains in a wetland. Determination of residence times within wetlands serves to define the role of wetlands as a transformer, producer, and water storage component in the overall landscape system. In general, longer residence times bring about greater transformation of materials passing through the system, but also bring about anaerobic conditions and low productivity. The rate at which water can flow across a wetland is controlled by ground slope, water depths, type and abundance of vegetation, and the degree and type of channelization. Residence time is defined as the ratio of total inflow rate to average volume within the wetland:

$$r = W/Q_t$$

where

r = residence time

W = average volume of water stored in the wetland

Q_t = total inflow rate

There are vast differences among wetlands in their residence times. These differences are controlled by physiographic features, drainage, climate, vegetation, and sediments. For example, some depressional wetlands remain relatively isolated from exchange with surrounding surface water and groundwater systems for several months a year, whereas tidal wetlands seldom retain water for more than a few days. Moreover, because water depths, substrate conditions, and plant types and densities across a wetland commonly vary widely, residence times are not uniform. Hence, residence time estimates are approximations at best (Mitsch and Gosselink 1993).

Evaluation of each of the components of the water budget (precipitation, ET, surface water inflow and outflow, and groundwater discharge and recharge), rainfall-runoff relationships, wetland water volumes and residence times, and their seasonal and annual variations provides the means to determine which hydrologic processes are critical to the maintenance and enhancement of particular wetland functions. Furthermore, integrated hydrologic analysis makes it possible to distinguish which atmospheric, geologic, and biologic components are critical to the maintenance and enhancement of hydrologic processes within a wetland.

6 Framework for Wetland Systems Management

This report has described physical processes that control wetland and landscape forms and functions. In addition, this report has presented various methods to monitor wetlands and landscapes and evaluate their interactions. The next step in developing a comprehensive wetland management program is to organize goals, resources, and information into a framework that serves as a guide for formulating a management plan, developing an initial database, and implementing a management program (Figure 44). Figure 44, in tandem with Table 21, provides a systematic guide for developing and implementing a program that is oriented toward managing wetlands in a landscape context. Considerations that are critical to a successful management plan are discussed below.

Formulating a Management Plan

Development of a wetland management program begins by formulating a realistic and viable, yet flexible monitoring and management plan. Formulating a management plan includes (a) defining underlying management concerns, (b) assessing available resources, (c) determining the size of the landscape to be evaluated, (d) establishing goals that focus on managing the wetland as an integral component of the landscape, (e) establishing an initial action plan that is capable of attaining the goals set forth and that is capable of evolving, (f) organizing management teams, and (g) establishing a continuing education program. These procedures are discussed below. It is important to realize that development of many of these steps occur simultaneously because decisions regarding one step are interrelated to formulation of other steps.

Regulations, orders, and environmental concerns that affect or could potentially affect management decisions should be identified. Changes in present management practices that are necessary to satisfy these directives should be identified. These mandates and concerns can serve as a basis for establishing goals of the program.

A viable wetland management plan must thoroughly consider available monetary, data, and personnel resources. The importance of this step can not

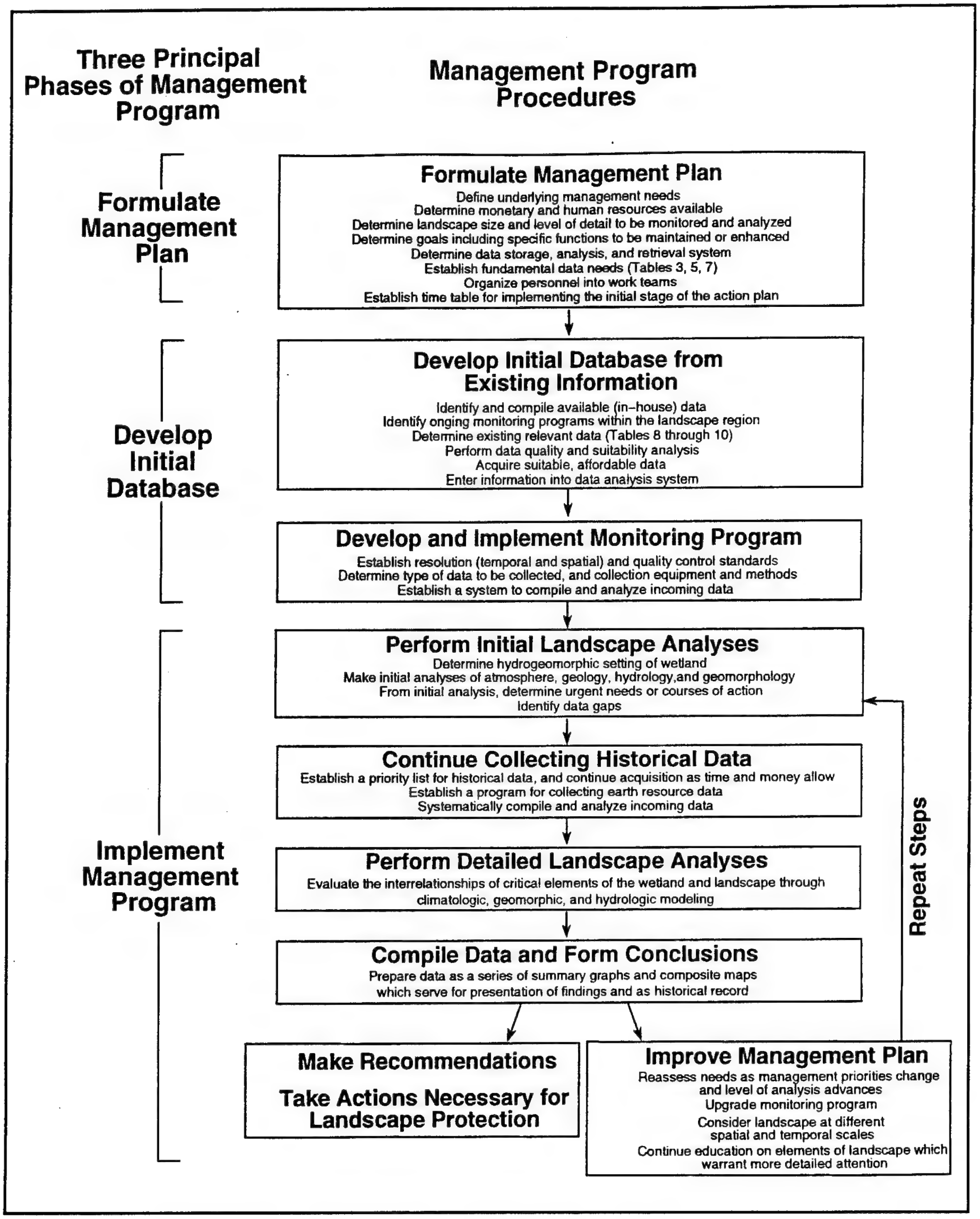


Figure 44. Framework for developing and implementing a wetland management program

be overemphasized because no matter how good a management strategy may seem, if resources are not available, the program will fail to meet the goals set forth. Careful assessment of resources is essential to formulating a management plan that takes full advantage of available assets without extending

Table 21
Developing a Framework for Wetland Landscape Systems Management

Technical Questions	Remarks and Suggestions
Formulate a Management Plan	
What set of circumstances prompted initiation of the program?	Clearly defining the environmental problem, set of regulations and concern of outside parties will help to define goals and priorities of the program (section entitled Formulating a Management Plan).
What are the fiscal, time, and personnel constraints?	A fundamental step toward development of a landscape management plan is to establish what resources are available for the program. This assessment determines the scale, level of detail, and degree of reliability of the results. Goals should be set that are attainable within the constraints of available resources. Clear, realistic, yet ambitious plan more likely will receive generous allocations of resources (section entitled Formulating a Management Plan).
What is the area to be to be evaluated?	Delineating the area to be monitored and evaluated involves defining the watershed area, deciding on the level of detail of monitoring and analysis that will provide the most information about wetland/landscape interactions for the amount of time and money invested (section entitled Landscapes as Systems).
How much emphasis is to be placed on specific wetland functions and on overall monitoring and analysis of the landscape?	Any program should have two primary goals: maintenance and enhancement of particular wetland functions, and monitoring and analysis of the landscape to ensure the overall health of the wetland. Stewardship of specific wetland functions dictates specific goals for the program. Overall monitoring and analysis of the landscape is necessary to ensure that cumulative impacts do not endanger the general health of a wetland.
What are the plans for further education in landscape analysis?	Because of the complexity of landscape analysis, members of the wetland management team should be provided with opportunities for continuing education. Education topics should suit particular problems of the landscape and the needs of the management team.
Data Suitability Analysis and Acquisition	
What data resources are already available?	Available resources include published maps and literature, colleagues and other contacts, and databases that the District or project partners have compiled. Historical data are expensive and time-consuming to compile. A realistic approach is to establish a long-term monitoring program and acquire and compile historic data as resources allow (see Tables 8 through 10 and section entitled Developing an Initial Database).
In what format are the data to be compiled, stored, and analyzed?	Table 7 outlines the essential data coverages for systematic landscape analysis. A program that uses Table 7 as a guide will help avoid gaps in data and analysis. Determine if the database is to be English or metric. It is customary to compile and store landscape information in tabular, graphical, and map formats. The advantages of a GIS to compile and analyze earth resource data in map form is discussed in the section entitled Geographic Information Systems. Formulation of a program should include decisions regarding table format and types of graphical methods. Other graph styles can be added as the program is refined and education level is enhanced.

(Sheet 1 of 9)

Table 21 (Continued)	
Technical Questions	**Remarks and Suggestions**
Data Suitability Analysis and Acquisition (Continued)	
How much do the data cost?	Early analysis eliminates data which are beyond budgetary means (sections entitled Formulating a Management Plan and Developing an Initial Database).
What is the original purpose of the database, and what type of information does it contain?	For data that are to be purchased, the appropriateness of the database or data layer content must be determined with respect to intended use. For example, are the data sample frequency suitable for this study?
What is the scale of the database in comparison to scale of study?	Data that are too large-scale will not provide necessary resolution; data that are too small-scale will cost too much to collect and analyze.
What methods were used in collecting, measuring, and analyzing data?	Appropriateness of data in terms of specific content should be determined. Do the data cover a sufficient length of time? Is depth of subsurface data sufficient?
How reliable are the data? Is documentation available that outlines data collection and quality assurance procedures?	Quality control must be commensurate with quality needed for present analysis and comparable to other databases used in the analysis. Is the real-time hydrologic and meteorologic data verified?
In what format are the data available?	Computerized data in formats not compatible with available equipment should be avoided. Cooperation with other organizations working in the area ensures that incompatible databases will not occur.
How do the various databases or data layers compare?	Determine if map projections for the different map layers are the same, the data are in English or metric units, there are differences in wetland delineation between NWI, soils, and available land cover maps, and how scales of analyses compare.
What and where are the data gaps?	Systematic use of Tables 8 through 10 should help identify data gaps. Once gaps are identified, a monitoring plan can be devised. Consultation with experts (e.g., climatologists, hydrologists) can lead to the use of proxy information, thereby avoiding expensive, direct monitoring activity.
What are the time, personnel, and cost constraints on collecting better data?	Determine how the costs and quality of existing data compare with the cost of collecting site specific, standardized data. Decide on a clear program plan, set of goals, and budget facilitates appropriation of resources and personnel.
Land Use/Land Cover	
What data sources are available to assess land use and land cover?	Data sources for land use and land cover are reviewed in Tables 8 through 10 and the section entitled Land Use and Land Cover.
What land cover classification is to be used? Which land use classification?	The Norton, Organ, and Litwin (1985) classification scheme is presented in the section entitled Land Use and Land Cover. However, classification choice depends upon scale of analysis and uniqueness of the landscape, especially with regard to land use and geographic location.
Are land use and land cover conditions stable in the landscape, or are they changing? What is the rate of change?	Changes in land use and land cover can be assessed using methods described in Chapter 4. In addition, comparisons can be made between land use and land cover changes to hydrographs, wetland stage records, sediment accumulation rates, and water chemistry (section entitled Surface water).
	(Sheet 2 of 9)

Table 21 (Continued)	
Technical Questions	**Remarks and Suggestions**
	Land Use/Land Cover (Continued)
Are there any major changes planned in land use and land cover?	Regional planners and county officials should be consulted to determine any development or restoration programs planned for the area.
	Climate
What are the precipitation characteristics?	Precipitation data can be compiled as average monthly or annual, in graph format to monitor trends, and in map format to monitor areal distribution. In regions with snowfall, extent, thickness, timing, and rate of snowmelt should be monitored (section entitled Precipitation).
What are the temperature characteristics?	Temperature data can be compiled in tabular form and compared to other parameters such as precipitation.
What are the water vapor characteristics?	If ET is to be evaluated in detail, relative humidity, dew point temperatures should be monitored (section entitled Atmospheric water vapor).
What are the wind flow characteristics?	Wind flow characteristics are best summarized by a wind rose (Figure 14 and section entitled Wind).
What are the characteristics of solar radiation?	Albedo and its seasonal variation should be monitored. The degree of cloudiness, which is a reliable measure of solar radiation budget (Mather 1978), should be monitored (section entitled Solar radiation).
What are the rates of evapotranspiration in the watershed?	The method of calculation and the instrumentation used should be identified. Ranges of errors should be estimated. The difference between monthly potential and actual ET should be monitored and recorded as an essential part of the landscape water budget. The relationship between potential and actual ET and soil moisture should be recorded as shown in Figure 28. The overall soil water budget can then be compared with wetland hydroperiods and other wetland functions (section entitled Evapotranspiration).
Which synoptic weather patterns (SWP's) commonly recur in the region, and what types of local weather are associated with these patterns? What are their frequencies of occurrence?	Figure 18 provides SWP's which control the climate of New Orleans, LA. As mentioned previously, these same patterns generally control weather for most of the conterminous United States. The resultant weather, however will be different for each region. Regional climatic data centers (Table 10) and geography departments of local universities can likely provide information on the synoptic climatology (section entitled Synoptic climatology).
Can the SWP's be grouped into meaningful climatic indices? What are their frequencies of occurrence?	Climatic indices are discussed in the section synoptic climology (Figures 19, 20). The climatic indices, however, for New Orleans are not necessarily applicable to other regions and therefore other sectors of the United States require region-by-region analysis.
What are the magnitudes of 1-, 2-, 5-, 10-, 25-, 50-, and 100-year storm events? What type of storms are they (frontal convergence, convective, orographic, upper atmospheric disturbance)? What synoptic weather pattern is associated with them?	Rainfall magnitude/frequency atlases are listed in the section entitled Precipitation. More specific magnitude-frequency-duration-timing of a climatic event in a particular landscape should be sought from regional climatologists. Information regarding the influence of storm events on flooding should be sought from regional hydroclimatologists.
	(Sheet 3 of 9)

Table 21 (Continued)	
Technical Questions	**Remarks and Suggestions**
Climate (Continued)	
What are the long-term weather trends?	Graphs such as Figures 19 and 20 are an effective means to monitor long-term weather trends. It is then possible to determine if weather trends correlate to trends in the wetland functions and other processes in the surrounding landscape (section entitled Synoptic Climatology).
What atmospheric phenomena are responsible for the formation of the wetland and, have they changed over time?	Detection of the atmospheric phenomena which brought about development of the wetland serves to identify critical processes in the landscape and establish long-term trends.
Geology and Soils	
What geologic data are available for the study area?	Geologic data sources are reviewed in Tables 8 and 10 and the section entitled Geologic Data Sources. Geologic data that should be compiled are reviewed in Table 10. Geologic information in the field is generally obtained from exposed sections along roads, railroad tracks, and streams, or from subsurface cores.
What is the structural setting of the landscape?	This includes folding, faulting, and tilting of the rocks and sediments. It is customary to summarize this information both in map and cross section form. The structural setting exerts a strong control on the hydrology and topography, i.e., drainage basin configuration (section entitled Prequaternary (or bedrock) geology).
What rock and sediment types occur at the Earth's surface (just below the soil horizon), and how susceptible are they to weathering and erosion?	A geologic map shows the distribution of rocks and sediments at the Earth's surface. A map scale >1:62,500 is required for meaningful landscape analysis. Weathering characteristics of rocks are briefly discussed in the section entitled Weathering.
How resistant are the rock types in the landscape to weathering and erosion?	Knowledge of rock type, their distribution, and susceptibility to weathering will facilitate evaluation of the sediment budget (sections entitled Prequaternary (or bedrock) geology and Erosion).
What is the distribution of unconsolidated late Pleistocene - Holocene sediments?	Because late Pleistocene - Holocene sediments underlie many wetlands, their 3-D distribution should be given special consideration. Many geologic maps are too generalized to differentiate late Pleistocene-Holocene sediments. Subdivision of these sediments generally requires coring and construction of cross sections (section entitled Quaternary geology).
What are the frequency and orientation of lineaments in the landscape?	Lineaments exert strong control on groundwater and stream flow direction. They are commonly identified from topographic and vegetal features on aerial photographs or topographic maps. Lineaments are commonly masked by sediment veneer (section entitled Prequaternary (or bedrock) geology).
What is the prequaternary history of the landscape region?	Understanding the extended history of the region provides insight into long-term geologic trends which may influence and even supersede shorter term climatic trends (section entitled Geomorphology).
	(Sheet 4 of 9)

Table 21 (Continued)	
Technical Questions	**Remarks and Suggestions**
	Geology and Soils (Continued)
What soil types occur across the landscape and within the wetland?	Soil distribution maps are available from local NRCS (formerly SCS) offices. The Hydrologic Group for each soil type should be ascertained. Soil classification systems are reviewed in Table 16 and Figure 25. The relation of soil types to weathering and climate is reviewed in Figures 26 and 27 (section entitled Soils).
What are the principal weathering processes in the landscape, and where are they taking place and at what rate?	Construction of a sediment budget and routing map are discussed in the section entitled Sediment routing and Budgeting. Weathering rates are controlled by material type, climate, relief, and the relative position in the landscape.
What are the weathering products?	Products of weathering include dissolved salts, clays, and quartz sand. In cooler, drier climates, weathered material may be coarser grained and only partially altered, hence retain some of the original mineralogy (section entitled Weathering).
What is the rate of soil loss?	Soil loss refers to removal of soil from a specific area without regard to the ultimate fate of the eroded portion. Equations such as the USLE are standard methods for evaluating soil loss (section entitled Erosion).
What are the sediment yields for the landscape?	Sediment yield refers to the transport of eroded material to or past some fixed point. Two common methods for estimating sediment yield are stream transport and reservoir accumulation rate estimates (sections entitled Erosion and Sediment Routing and Budgeting).
What are the rates of denudation?	Rates of denudation, or geologic erosion, are long-term rates of removal of material from the landscape. Denudation includes not only surficial erosion but also mass movement (section entitled Erosion).
What are the principal transport agents?	Overland and channel flow are the principal surficial agents for transporting sediment. Wind can also be a significant surficial transport agent, and groundwater can be an significant subsurface transport agent, especially of dissolved ions (section entitled Transport).
What are the principal routes of sediment transport through the landscape?	Budgets should be evaluated in terms of rates rather than volumes. Evaluating routes and frequencies should take into account the mechanisms which transport sediment and their frequency of occurrence (section entitled Sediment Routing and Budgeting).
What are the transport rates of sediment through the landscape?	Determining sediment transport rates through the landscape is an essential step in calculating sediment budgets (sections entitled Transport and Sediment Routing and Budgeting).
Where are the areas of temporary storage, and what are their residence times? What proportion of the landscape sediment budget do they hold?	There is no clear distinction between areas of low transport rates and areas of temporary storage. Identifying and evaluating areas of temporary storage is essential to analyzing the flow of materials though a landscape (sections entitled Storage, Sediment Routing and Budgeting, and Magnitude-Frequency Analysis).
Where are areas of long-term sediment storage and what proportion of the landscape sediment budget do they hold?	Areas of long-term storage are important for evaluating the landscape sediment budget, and are the primary source of information regarding the history of the landscape (sections entitled Sediment Routing and Budgeting and Magnitude-Frequency Analysis).
	(Sheet 5 of 9)

Table 21 (Continued)

Technical Questions	Remarks and Suggestions
Geology and Soils (Continued)	
How are materials transformed in the temporary and long-term storage areas?	Transformation of sediment has a strong influence on near surface groundwater chemistry.
What role does the wetland have in transformation, transport, and storage of sediment in the overall landscape system?	Evaluating the role of the wetland in processing material through the system is an essential step toward understanding wetland functions in the context of the larger landscape.
What geologic phenomena were responsible for the development of the wetland, and have they changed over time?	Detection of the geologic phenomena which brought about development of the wetland serves to identify critical processes in the landscape, and establish long-term trends. Knowledge concerning the origin of the wetland may provide insight into water sources, retention time of sediments, and rates of modification of wetland form and function.
What is the hydrogeomorphic setting of the wetland?	Defining the hydrogeomorphic setting of a wetland is an initial step toward defining the role of wetlands in the landscape (section entitled Wetlands as Hydrogeomorphic Systems).
What is the size of the wetland relative to the watershed?	This ratio provides insight into the relative importance of the wetland in the flow of energy and materials through the landscape.
Is the landscape relict (generally from the last glacial epoch) or in dynamic equilibrium?	Ascendancy of dynamic equilibrium over relict conditions is largely a function of the ratio intensity of forces acting upon the landscape and the capacity of the landscape to resist to change (Chapter 4). In many landscapes, there is a spectrum of landforms in which completely relict and completely in equilibrium are the end points (section entitled Equilibrium States).
Where are areas of constructional and destructional landforms?	This information is contained on the sediment routing/budgeting and landscape geomorphology maps. Using these maps landforms are matched erosion and accretion rates to create a new map - landform change map.
What is the order of streams located in the landscape?	Stream order values indicate the relative position in the drainage basin. A wide range of stream orders indicates a well developed landscape (section entitled Watershed Morphometry).
What is the stream density?	Stream density is a function of the ratio of runoff to infiltration. Other factors which influence drainage density include climate, relief, and geology (section entitled Watershed Morphometry).
What is the bifurcation ratio?	The bifurcation ratio indicates the relative proportion of surface runoff and seepage (section entitled Watershed Morphometry).
What is the effect of relief?	Relief controls the relative proportion of surface runoff and seepage (section entitled Watershed Morphometry).
What is the relief ratio of the drainage basin?	The relief ratio evaluates the relative impact of basin length and relief to surface water runoff (sections entitled Watershed Morphometry).
What is the elongation ratio of the watershed?	The elongation ratio determines how quickly storm water is drained from a watershed (section entitled Watershed Morphometry).
	(Sheet 6 of 9)

Table 21 (Continued)	
Technical Questions	**Remarks and Suggestions**
	Geology and Soils (Continued)
What is the ruggedness number?	The ruggedness number evaluates the relative impact of drainage density and basin relief to surface water runoff (section entitled Watershed Morphometry).
What is the Flash Flood Magnitude Index (FFMI)?	The FFMI indicates the rate of geomorphic change in a landscape (section entitled Magnitude-Frequency Analysis).
What are the equilibrium states of the soils? If disturbed, how much time have the soils had to reequilibrate? If disturbed, how do present erosion rates compare to erosion rates before disruption?	Comparison rates for natural versus disturbed soils in the landscape, and evaluation of the areal extent of disturbed soils provides insight into the equilibrium state of the landscape system. This is simplified by calculating the Curve Numbers (CN's) for the various landscape soil types (Table 12) and monitoring their change over time. Because erosion is a function of runoff, changes in CN's are related to sediment yield (section entitled Magnitude-Frequency Analysis).
What are the magnitude, frequency, duration, and timing of events which cause erosion? In particular, what are the erosion rates and sediment yield associated with 1-, 2-, 5-, 10-year etc. storm events?	Analysis of erosion rates as a function of storm events contributes to the prediction of the flow of materials through the landscape (section entitled Magnitude-Frequency Analysis).
What are the magnitude, frequency, duration, and timing of events which transport stream sediment?	Analysis of erosion rates and sediment yield as a function of storm events enables prediction of the flow of materials through the landscape. FFMI's are a good indicator of the intensity of atmospheric processes acting on the landscape (section entitled Watershed Morphometry).
What are the magnitude, frequency, duration, and timing of events which move materials into and out of storage areas?	Analysis of erosion rates as a function of storm events enables prediction of the flow of materials through the landscape. This information compiled and stored on the sediment budgeting/routing map (sections entitled Sediment Routing and Budgeting and Magnitude-Frequency Analysis).
Are there notable changes in the wetland hydrology and (or) ecology which appear related to changes in environmental baseline indices (synoptic weather types)? Are these of annual or decadal scale?	This analysis requires compilation of meteorologic, hydrologic, and ecologic data, and is best carried out in a GIS format. This information is also compiled and stored on the sediment budgeting/routing map (sections entitled Synoptic Climatology and Magnitude-Frequency Analysis).
Are there forces or processes external to the landscape, such as pollution, which are a important factor in the wetland landscape?	Landscapes should be analyzed at a variety of scales because the scale of processes acting on them is so highly variable.
In what way does the wetland serve as a source, sink, transformer, amplifier, resistor, capacitor, catalyst, and buffer to the surrounding landscape?	Wetland processes and/or components that serve as a source, sink, transformer, amplifier, resistor, capacitor, catalyst, and buffer to the surrounding landscape should be identified and recorded. The capacity of the wetland to interact with the landscape in these fashions should be evaluated and monitored over time (section entitled Wetlands as Systems).
	(Sheet 7 of 9)

Table 21 (Continued)	
Technical Questions	**Remarks and Suggestions**
	Geology and Soils (Continued)
In what way does the landscape serve as a source, sink, transformer, amplifier, resistor, capacitor, catalyst, and buffer to the wetland?	Landscape processes and/or components that serve as a source, sink, transformer, amplifier, resistor, capacitor, catalyst, and buffer to the wetland should be identified and recorded. The capacity of the landscape to interact with the wetland in these fashions should be evaluated and monitored over time (section entitled Wetlands as Systems).
	Hydrology
Which hydrologic components are being monitored in or near the study area?	Hydrologic data should be compiled at least on a monthly basis. Locations and types of instruments used to monitor the hydrology of the landscape should be recorded on the Hydrologic Instrument Location Map (Table 7).
What other hydrologic data is available for the study area?	Hydrologic data sources are reviewed in Tables 8 and 10 and in the hydrology section of Chapter 5. Essential hydrologic data are reviewed in Table 7.
What is the quality of preexisting data?	Existing hydrologic data should be carefully assessed to determine that the instruments were accurate and consistent (i.e., that the types of instruments being used were the same over time, or if changed, were calibrated). Moreover data should be checked to determine that measurements were taken at a frequency that is meaningful to the management program and that data are representative of ambient conditions (e.g., staff gages are located in portions of the stream that reflect overall stream conditions).
What are the hydrograph signatures for the landscape and how do they compare to associated hyteographs.	Hydrographs and associated hyteographs (Figure 13) should be compiled on a systematic basis, if possible, from several positions in the landscape. They are an effective means to monitor change in the rainfall-runoff relationship over time (section entitled Stream flow).
Which hydrological processes are responsible for wetland formation, e.g., channel switching, rise in groundwater table?	Determination of the hydrologic components which initiated wetland development will help define which components are forcing functions (section entitled Magnitude-Frequency Analysis).
What is the general distribution of surface water flow in the watershed?	Routing of overland as well as stream flow should be mapped. This will aid in the determination of sediment routing (section entitled Surface water).
What is the variability of stream flow? Has it varied over time?	Analysis should include monthly averages, base flow, and long-term peak flow (section entitled Stream flow).
What is the average residence time of water in the landscape, and how does this compare to residence times in the wetland?	Assessing residence times serves to define the flow of energy and material through the system. Residence times should be considered for both surface and groundwater (section entitled Surface water).
What is the variability of wetland water levels? What is the hydroperiod? How do wetland water levels affect the flow of materials and energy through the landscape?	Monitoring wetland water levels provides a means of gauging the health of the wetland: it also provides a measure of the role of the wetland in the landscape hydrologic cycle. A simple method of monitoring wetland water levels on a long-term basis is presented in Figure 43 (section entitled Wetland water circulation).
	(Sheet 8 of 9)

Table 21 (Concluded)	
Technical Questions	**Remarks and Suggestions**
Hydrology (Continued)	
What is the magnitude, frequency, and timing of flood events?	Analysis should not only include compilation of hydrologic data, but also anecdotal evidence, such as old newspapers accounts of major storm events (sections entitled Magnitude-Frequency Analysis and Stream flow).
What aquifers underlie the landscape? What is their porosity and permeability. What are their geometries? Are they stratified or homogeneous? Are the aquifers confined or unconfined?	Some aquifer characteristics are discussed in the geology portion of this table. Analysis of shallow aquifers is discussed in the section entitled Groundwater.
Where are the areas of groundwater recharge for the aquifers. What is their land cover and land use?	Defining areas of groundwater recharge serves to define the groundwater drainage basin and determine the position of the landscape in the local, intermediate, and regional groundwater flow system (section entitled Groundwater).
What is the relative position of the landscape and wetland in the local, intermediate, and regional groundwater flow system?	Defining the position of the wetland and overall landscape in the groundwater flow systems serves to evaluate the relative importance of groundwater flow in the wetland water budget (section entitled Groundwater).
What are the principal hydrologic cascading systems? How does the wetland fit into this cascade (sink, transformer, amplifier)?	Evaluation of the flow of energy and material through the landscape should reveal the principal flow paths of water. Evaluation should also reveal the role of the wetland in these principal flow paths. Construction of flow charts similar to Figure 35 may be useful in characterizing principal hydrologic cascades (section entitled Hydrologic Components of Water Budgets).
	(Sheet 9 of 9)

beyond available means. A simple but comprehensive plan that can be realized is better than an elaborate plan in which portions must later be curtailed or aborted because of lack of resources. Early recognition of those phases of the program (monitoring, preprocessing of GIS data, etc.) that will be resource intensive and careful evaluation of their cost in terms of time and money can serve as a basis for determining the scale and depth of detail of monitoring and analysis in the management program.

Defining the landscape area to be monitored and analyzed begins by (a) considering available resources, and (b) delineating the drainage basin that contributes surface water flow to the wetland. As mentioned in Chapter 2, the drainage basin is the fundamental unit for landscape evaluation. However, it may not be feasible nor advisable to directly monitor the entire watershed, particularly in the case of riverine wetlands and tidal marshes in the lower reaches of major rivers. If the entire drainage basin is not to be evaluated, the landscape area should be a coherent subbasin with clearly defined boundaries. Seabar, Kapinos, and Knapp (1987) provide guidelines for defining drainage basins and subbasins. In all cases, principal attributes of the entire drainage basin should be characterized (land use, land cover, position of the wetland in the watershed, etc.). In addition, regional observations, such as

synoptic weather patterns (Figure 18) and the affects of el Niño, should be monitored to evaluate large-scale trends on landscape form and process.

Formulating goals must take into account underlying management concerns and available resources. All management programs should include two fundamental goals: (a) maintenance and enhancement of particular wetland functions and (b) monitoring and analysis of the surrounding landscape to ensure the overall welfare of the wetland. Consideration of wetland/landscape interactions, as described in Table 5, serves to establish management goals in a landscape perspective. Goals should incorporate the objectives of environmental programs being carried out in the area by other Federal, state, or local agencies (Table 9), and include partnerships with these organizations. Goals should include a timetable which specifies when particular tasks (collection, compilation and analysis of historical data, compilation of land cover and land use maps, etc.) are to be completed. When defining goals, it is essential to keep in mind that the cornerstone of the program is to manage wetlands and wetland functions in a landscape context.

After assessing available resources and defining goals, an initial working plan can be formulated. Essential elements of the working plan include: determining scales and resolution of analysis, types of analysis to be performed, type of data management and analysis system to be used, initial data needs, and timetable of initial analysis (Figure 44). To develop plans that engender wetland management in a landscape context, a broad range of atmospheric, geologic, hydrologic, and biologic phenomena must be evaluated (Table 21). Formulating effective management plans requires that the hydrogeomorphic setting of the wetland be identified. Plans should include provisions to identify hydrologic components (Figure 3) that are critical to the welfare of the wetland and evaluate landscape parameters that control these critical hydrologic processes (Table 3). Plans should include provisions to identify and evaluate elements of the landscape that most influence wetland functions (Table 6). Having initially identified landscape processes that are critical to wetland forms and functions, data coverages (Table 8) that are essential to the management program can be identified.

Plan formulation is an iterative process. For example critical hydrologic components of the wetland must be identified and to some degree evaluated before plans can be formulated to identify the landscape parameters that are critical to those hydrologic components (Table 3), and the critical landscape parameters must be identified before plans can be formulated to evaluate those landscape parameters.

The management plan should include specific assignments to available personnel. Each person's role should be clearly defined, and the time each team member is to devote to the program should be clearly stipulated. To promote wetland management in a landscape context, personnel should be assigned to work in multidisciplinary teams in an environment in which interaction is fostered. Assessment of available human resources should reveal educational needs of available personnel. The management plan should include provisions to satisfy these education needs.

Developing an Initial Database

Having developed a working plan, detailed assessment of data needs is the next step in implementing a management program (Table 21). This phase includes identifying relevant in-house data, locating pertinent, preexisting data (Table 10), and assessing the suitability and cost of available data. Databases must be thoroughly examined to determine quality of terms of accuracy of measurement, frequency of sampling, and the degree they reflect ambient conditions. Data collection and compilation are costly and time-consuming; it is unlikely that all relevant data can be immediately purchased and compiled. Hence, time and money should be allocated for ongoing data search, collection, and compilation. Priorities should be established to define the order in which data are to be purchased and compiled. Suitable data should at least be identified as soon as possible so that monitoring needs can be defined.

After available data have been assessed and inventoried, and essential aspects of the landscape that lack data or are poorly understood have been identified, a monitoring program may be established (Figure 44). Recognizing data needs requires understanding of those landscape processes that are critical to wetland hydrology (Table 3), and to maintenance and enhancement of desired wetland functions (Table 6). Landscape processes that are most commonly monitored include: precipitation, ET, temperature, wind speed and direction, sedimentation rates, stream discharge, and groundwater movement. Monitoring programs should also include plant and animal diversity/abundance, and threatened and endangered species inventories.

The work plans should specify which data coverages (Table 7) are to be compiled. However, as understanding of the of landscape processes that are critical to the wetland increases, the data coverage list will need to be modified. In addition, as the management program evolves, monitoring can be enhanced, and therefore monitoring systems should be designed for later expansion. For example, piezometer nests should be arranged so that additional piezometer nests can be placed in hydrologically meaningful locations.

Implementing the Management Program

After a significant portion of the preexisting database together with preliminary information from the monitoring program is compiled, initial landscape evaluation may proceed (Figure 44). Evaluation is based upon addressing the questions in Table 21. Initial analysis serves to identify serious problems which warrant immediate attention (i.e., water-level fluctuations that inhibit nesting or plant germination, sediment loadings which endanger vegetation or fish populations, anomalously high nutrient levels). Preliminary analysis serves to identify elements of the landscape which are poorly understood and require further attention (i.e., those questions in Table 21 that are poorly answered). Initial analysis also serves to identify landscape processes that are most critical to maintenance and enhancement of specific wetland functions, and to evaluate landscape and wetland equilibrium. Preliminary analysis also

serves to determine which methods of analysis, and which climatologic, geomorphic, and hydrologic models are most appropriate for detailed evaluation.

The monitoring and analysis program promotes understanding of the landscape's hydrologic cascade system and the position and role of the wetland in this system. The monitoring and analysis program should focus on the flow of material and energy through the landscape system, and how the role of the wetland (Table 5) in this cascade. The monitoring and analysis program should evaluate the impact of disturbances, such as storms and land use changes, on the flow of material and energy through the system, and how these modifications impact wetland forms and functions. These observations serve to identify critical processes affecting wetland functions, landscape equilibrium, frequency and type of agents that cause significant changes in the wetland and landscape, and the influence of humans on the wetland. With an understanding of process-response relationships within a landscape, an effective management strategy can be developed which considers the wetland as an integral part of the landscape.

An effective management program includes ongoing search, acquisition, and compilation of historical data (Figure 44). Monitoring information, such as aerial photographs and stream gage data, are conducive to annual- and decadal-scale analysis. Geologic information, such as sediment cores is conducive to centennial- to millennial-scale analysis. Because most wetlands in the United States developed after the end of the last glacial period, geologic analysis should concentrate on the Holocene epoch. Evaluating the long-term history of the wetland provides a baseline to monitor the impact of disturbances that recur every 2, 5, or 10 years (Section entitled Magnitude-frequency analysis).

As data continue to be compiled, or as management needs warrant, the landscape is reevaluated (Figure 44) which typically comprises readdressing the questions in Table 21, and compilation of summary graphs (e.g., Figures 13, 14, 19, 20, 28, 36, 40, 43) and composite maps (using the GIS). The management strategy should include periodic reevaluation of the monitoring program, and, as management concerns change and understanding of the wetland landscape evolve, goals of the program should be reassessed and modified.

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REPORT DOCUMENTATION PAGE

Form Approved
OMB No. 0704-0188

1. AGENCY USE ONLY *(Leave blank)*

2. REPORT DATE
October 1995

3. REPORT TYPE AND DATES COVERED
Final report

4. TITLE AND SUBTITLE
Framework for Wetland Systems Management:
Earth Resources Perspective

5. FUNDING NUMBERS
Work Unit 32766

6. AUTHOR(S)
Andrew G. Warne, Lawson M. Smith

7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)
U.S. Army Engineer Waterways Experiment Station
3909 Halls Ferry Road
Vicksburg, MS 39180-6199

8. PERFORMING ORGANIZATION REPORT NUMBER
Technical Report
WRP-SM-12

9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)
U.S. Army Corps of Engineers
Washington, DC 20314-1000

10. SPONSORING/MONITORING AGENCY REPORT NUMBER

11. SUPPLEMENTARY NOTES
Available from National Technical Information Service, 5285 Port Royal Road, Springfield, VA 22161.

12a. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution is unlimited.

12b. DISTRIBUTION CODE

13. ABSTRACT *(Maximum 200 words)*

It is widely acknowledged that effective wetland management must be done in a landscape context. Until now, however, there has not been a systematic approach to evaluating and managing wetlands and their functions as interactive components of the broader landscape. A conceptual and methodological framework is presented to serve as a comprehensive guide to wetland management. The framework recognizes that wetland landscapes are the product of interaction among atmospheric, geologic, hydrologic, and biologic materials and processes. Over time, changes in these interactions modify the flow of energy and material through the landscape causing wetlands to adjust to new equilibrium states. Hence, the management framework provides methods to monitor and evaluate the atmosphere, geology, and hydrology of a landscape to evaluate how these spheres of influence interact to produce wetland conditions. Such geomorphic evaluation reveals those factors that are critical to the maintenance and enhancement of wetland functions, thereby identifying processes and components of the landscape that warrant particular attention and protection measures.

Using geomorphic analysis as a basis for decision making, the framework provides guidelines for locating and compiling existing data and assessing fiscal and human resources that are available for wetland landscape management. It provides guidance in establishing priorities and goals for management plans. The framework provides

(Continued)

14. SUBJECT TERMS
See reverse

15. NUMBER OF PAGES
154

16. PRICE CODE

17. SECURITY CLASSIFICATION OF REPORT	18. SECURITY CLASSIFICATION OF THIS PAGE	19. SECURITY CLASSIFICATION OF ABSTRACT	20. LIMITATION OF ABSTRACT
UNCLASSIFIED	UNCLASSIFIED		

13. ABSTRACT (Cont'd)

specific guidelines for implementing long-term management programs that are capable of evolving as the database and understanding of the landscape increase.

14. SUBJECT TERMS

Climatology	Meteorology
Geology	Systems approach
Geomorphology	Wetland landscape interaction
Hydrology	Wetlands management